Conclusions: 3D printing technologies in the food system for food production and packaging

In this section we present a summary of the main findings of this research, discuss implications for the FSA under consideration of its remit, and give general and specific recommendations that my inform future interactions of the FSA with an emerging 3DFP ecosystem.

7.1 Summary of main findings

Technology evolution

The technology initially started out over 15 years ago by explorative technologists, curious scientists and enthusiasts trying to use foodstuffs for printing on 3D printers that were developed for other materials. The early food ingredients used were chocolate and sugar pastes. Over the past decade, and in particular over the past 5 years a rapid increase in R&D efforts in research institutions as well as in a small number of startups and larger food processing and kitchen appliances companies has shifted the technology focus from decorative, “fun” and curiosity food items towards the printing of healthy foods, and foods for specific needs, such as for dysphagia patients. Diversification of printed food ingredients has also made clear that the optimisation and pre-processing of food inks are crucial steps for printing success, hence pre-processing needs to be considered an integral part of the technology. Also many novel printed food ingredients require post-processing, which in some instances also need to be considered an essential part of the printing process.

Besides a small number of startups that have driven the evolution of the technology, large food companies have shown a low level engagement with the technology for around a decade. For example Barilla, an Italian global leader in pasta production, has in collaboration with TNO, a Dutch research organisation, developed 3D pasta printing technology and has since offered 3D printed pasta through its subsidiary BluRhapsody. Another example of a large food manufacturing company collaborating with a 3DFP company startup is the collaboration between Verstegen, a Dutch sauce and soup manufacturer with byFlow, a Dutch food tech company with self-developed 3D food printers aiming to sell 3D food printers together with pre-prepared food paste cartridges.

Potential wider Impact of 3DFP

Despite some technological progress over the past decade, still only a small number of 3D printers have matured from the conceptual prototype stage to commercially available and viable products, most of them only in limited numbers in the context of semi-commercial startup settings. The most widely printed foods are still chocolate and sugar-based ingredients. Very recent developments enabling the printing of healthy ingredients, such as fruits and vegetables may enable a market for children or for food for the elderly and patients with difficulties swallowing. Other foods currently printable at small scale are cultured (in-vitro) and plant-based meat, pasta, dough-based baked foods and cheese. One of the key challenges of the technology is the need of adaptation and optimisation of printers to each food type as there is at present no universal 3D food printer that can print multiple food types at scale. Such multi-food printers, which are capable of printing more complex foods however, are at the prototype stage and may reach the market in the next five to ten years.

Wider systemic impacts of 3D printing of food are discussed in the academic literature and diversification of the technology through innovation into specific sub-niches indicate that 3D printing might act as an enabling or supporting technology for other technology-enabled trends in the food system, such as personalised nutrition, alternative proteins, use of food side- or waste streams, plant based meat alternatives, cultured meat, functional foods and health nutrition. Moreover, food printing currently appears to evolve from a focus on the shape aspect of printing towards finding solutions for real food processing challenges. This includes prototyping of novel foods to for example increase healthy ingredients such as fibre, or reduce salt, sugar and fat intake via printing of specific textures that modify the sensory experience of food. In the academic and grey literature claims are made about the future potential impacts of 3DFP around its ability to possibly increase sustainability of food production in some cases, or that it might enable business models of decentralised food production affecting supply chain models. Although such claims have been made repeatedly in the academic literature, supporting evidence is currently lacking due to the early stage of the technology and a lack of assessment frameworks.

3D printing for the production of food packaging

Information on the use of 3D printing technologies for the production of food packaging or food contact materials is at present scarce, but can be grouped into four categories:

- 3D printing used for prototyping in the food packaging industry:
- Large food packaging producers use 3D printing routinely for prototyping food packaging such as jars, containers, bottles etc, but use other mass production technologies to manufacture the final product.
- 3D printing used for the manufacturing of primary food packaging:
- Apart from small startups using 3D printers to test novel packaging concepts with novel (for example sustainable) materials, large packaging producers see 3D printing still as not suitable for the actual production of packaging due to its low performance and high costs compared to established manufacturing technologies.
- 3D printing as a proposed application for the production of “smart” packaging:
- Very limited academic research has tested possibilities to manufacture smart packaging elements with 3D printers. However, at current state of the technology it is unlikely that 3D printers can be used for mass production of such smart/intelligent packaging elements in the near to medium term future.
- 3D printed objects as food contact materials in applications other than packaging:
- Several examples of 3D printed food contact tools used sometimes at industrial scale have been identified, however none of these were of importance for packaging applications.

In summary, 3D printing technologies are not expected to contribute significantly to the production of food packaging in the mid to long-term future.

R&D developments in 3D food printing

R&D activities have been continuously increasing in the past decade, although from a very low base, with a sharp increase over the past five years and a number of R&D clusters are now well established, driving future developments of the technology. Research institutions outside of China with a strong focus in 3DFP are for example University of Queensland, Australia, McGill University, Canada, and Wageningen University, 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. Recent technology innovation is mainly focusing on making new and healthy food ingredients that have not been printed in the past printable and on improving robustness as well as throughput of the printing process. Progress in these areas may enable some applications to enter niche markets such as personalised foods, or foods for patients with swallowing difficulties at a larger scale.

Printers

Reviewing the food 3D printers currently available on the market it becomes clear that the choice is limited and defined by optimised print input 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, however, over the past five years there have been considerable efforts to advance the technology to enable printability at scale with other food materials, such as different dough and starch based foods, vegetables, alternative proteins from plant based sources, 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.

3D food printing market

Looking at the numbers for the potential addressable market size for industrial 3D printing/additive manufacturing may explain the small numbers of printers on the market and the fact that a number of former food printer companies have failed after a few years trying to turn a profit. Current estimates of the 3DFP market are in the range of $201m in 2022, and is estimated to reach $1.9bn by 2027 with a CAGR of 57.3%. This compares to the wider 3D printing market at between $8.6bn and $12.9bn with a projected CAGR of 18.2-22.5% until 2026. Clearly the estimated market is at present small by dimensions, however there is an optimistic view of its growth rate, despite the well-known challenges the technology faces.

Startups

Besides a small number of 3D food printer manufacturers that sell their printers, there are a number of businesses that use 3DFP to sell specific experiences or personalised food items. These so called concept startups are
currently exploring different business models and products to find an entry point for the technology into wider consumer markets. 3DFP concept startups can be divided into two groups by the type of printer they use or sell, namely either their own self-developed 3D food printers, or universal printers adapted for food printing. Irrespective of printer type, concept startups sometimes offer food and dining experiences that include personalised food items as part of the experience, or showcases the actual printing process. Such companies often operate only temporarily at events or in collaboration with restaurants.

Business Models

Due to the nascent nature of the sector, there has not been much empirical research into real-world emerging business models as the current evidence base is slim, although some academic investigation of the issue has started over the past five years. Authors agree that the technology still faces a number of challenges to adoption and scale, despite the technological progress in the past decade. The challenges are mainly around the following issues:

- 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

As a result of these challenges the technology has been so far limited to specific 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 through enabling:

- 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 own survey of 3DFP companies (see Appendix A, tables 6, 7, 8), 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

Like 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. Expansion and further integration of this ecosystem currently faces key business challenges, namely the absence of clear markets for products and services besides the low performance of the technology, in particular the slow printing speed.

Sustainability

A potential for increasing the sustainability of the food system is one of the claims advocates of the technology make occasionally, which is also discussed in the academic and grey literature. However, evidence for these claims are scarce or non-existent and there is no evidence based analysis or measurement framework to assess sustainability parameters of the technology at this point in time. The potential sustainability impacts of the 3DFP technology are often stated as (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

It has to be stated that a small number of academic authors point out the need for clear sustainability evaluation criteria as well as validation of the claims through relevant life cycle analysis for 3D printed foods from pre-printing processing of food pastes to post printing processes for making the product edible. Currently one Dutch startup, Upprinting Food, experiments with the up-cycling of retail bread and vegetable waste streams using 3DFP.

Consumer trends

Since its emergence as a tool to create unique designs for niche applications often in the confectionery sector, 3DFP has not made much progress with wider consumer adoption. Therefore, a number of players active in the field are aiming to position the technology around its ability to deliver personalisation for individual food and nutritional requirements. However, despite a general growing interest in personalisation options for food, 3D printed food is currently still unknown to most consumers.

Very limited consumer studies have also shown that Novel Food Technology Neophobia is a significant barrier to acceptance of 3DFP with the expectation of ‘naturalness’ of food being one of the biggest barriers to the willingness to try 3D printed food, which is perceived by many as not natural. Hence, consumer acceptance still remains a challenge for the sector and will require clear communication and trust building with consumers to advance wider acceptance of 3D printed foods. Furthermore, our own analysis of expression of consumer interest in 3DFP on social media has shown that there is no evidence that consumer push might be able to contribute to the evolution of the technology.

Regulation

Currently there is no regulation anywhere in the world that directly targets 3DFP technology and processes. Literature on potential regulatory issues is sparse. Nevertheless, both academia and industry are aware of the role that regulation could play for the growth of the industry. In discussions of European experts the focus is on the novelty aspect of the 3D printed foods and the related labelling and food safety considerations. Given that the EU has relevant legislation around novel foods, namely the EU Novel Foods Regulation 2015/2283 update 2018, the debate is mainly around whether this legislation suffices for regulating 3DFP products, or whether there is a need for specific regulation aimed at 3DFP. In the US academic literature on potential regulatory issues of 3DFP the focus is on food safety issues around the technology and the fact that there is no scientific evidence base to provide a baseline understanding of what required food safety parameters would be, should the technology reach maturity and reach wider consumer markets. Concerns have been raised also with regards to a lack of evidence for long-term health impacts of 3D printed foods, also due to the requirement of additives in many printed foods to aid the printing process. It is also acknowledged that early engagement of regulators could help set standards and in fact support the future evolution of the technology and build consumer trust.

7.2 Implications and recommendations for FSA

As the technology advances and potentially overcomes current barriers to scale it may enter larger markets with a variety of food items and its impact on the food system may grow. This means with regards to all main areas of concern for the FSA, namely food safety, authenticity, health and sustainability there will be a number of key aspects of 3DFP to consider when deciding on regulatory interventions.

3DFP is still at an early stage of maturity and will require time (5-10 years) to become more established as a food processing technology with a defined role in the food system both in B2B and B2C markets, with possibly B2B being commercially viable before B2C.

- The technology still faces a number of technical and societal challenges, mainly:
- Slow speed of production
- Upscaling the technology is challenging and in its current form only possible through ‘printer farms’
- Requirement for expert pre-processing of foodstuffs into a printable food ink

- This step also entails the often essential addition of known food additives or novel substances to help viscosity and other parameters of the food paste to enable printability
- Consumer perception of 3DFP is at present not necessarily positive
- Consumers have a much more favourable view of 3D printing when it comes to printing chocolate and sugary decorative objects. However, skepticism is high when other food materials are to be printed with the intention to represent a main part of a meal
- 3DFP is often presented as best applicable to personalisation and customisation of food products and most new startups develop their products around narrow niche applications. Hence, there is at present no well-defined rapid growth market that would help the technology grow.
- Currently 3DFP technology is moving from the R&D and prototype stage to wider commercialization with the focus of technology development on making more food ingredients printable. Therefore the question of whether 3D printed food is safe to eat especially as a main meal in larger quantities and for long periods of time has not been considered yet in earnest or researched - and will be difficult to do before the technology has evolved further.
- Sustainability claims around the technology still require validation and will be strongly impacted by how supply chains and business models evolve.
- Food safety issues are likely to arise in two key parts of the 3DFP process, namely preparation of the food inks and the printing process itself, depending on printer type, temperature and time required for preparation and printing. In addition, optimisation of post-processing steps is important, as they can help address some of the food hygiene/safety issues.
- Business models and supply chains for 3DFP are not yet well defined and will impact the further development of the technology
- The key technical factor that will impact how business models will develop is the need for adapting food ingredients for printability in specific printers, which usually requires considerable prior R&D efforts or expert support.

Given that one promoted advantage of the technology is in enabling customisation and personalisation of products, it is highly likely that in such application areas production will be carried out in batch mode rather than in continuous process mode. This will pose its own challenges such as the requirement for full cleaning of printers after each batch as potentially ingredients and safety profiles between batches may vary, for example with respect to contaminating allergens or ingredient sensitivity to pathogens etc.

3DFP using food inks made from food waste/side streams or for repurposing food that is near its sell by date will require extra measures to ensure safety and authenticity of ingredients. Furthermore, the types and amounts of additives that are required to increase shelf life of pre-prepared food ink cartridges (which are now offered by some printer manufacturers together with printers) are currently not standardised and not tested for their health impact when consumed in larger quantities for longer periods of time.

Process hygiene for 3DFP is of a different scale compared to many other food processing methods, with multiple small and narrow parts in the printer including nozzles, tubing, mixing mechanisms etc., which are difficult to access or inspect on a routine basis, especially by non-experts. Given that currently the printing process is slow, the food material is exposed to ambient atmosphere and printer temperature for longer periods which itself may cause propagation of microorganisms. Furthermore, the porous nature of the printed food material may provide growth cavities for microorganisms. Hence the importance of optimisation and validation of the post-printing process steps to bake, freeze, fry or dry the products.

Advocates of the technology strongly emphasise the potential for the technology to have an impact on sustainability of the food system by bringing supply chains closer to consumers and reducing food miles, or its potential to repurpose food waste or near end of use food into new products. However, such claims are not proven and sustainability assessment criteria for measuring and comparing 3D printed food products with otherwise processed equivalents are currently lacking. It is likely that similar to other process technologies, energy, water and industrially produced additives will be used in considerable quantities and setting up ‘printer farms’ to scale the technology may in itself pose other sustainability challenges.

7.2.1 General recommendations for consideration

Given that commercial 3DFP is nascent and the ecosystem of commercial players has not matured sufficiently, it is difficult to immediately identify the hubs and nodes or entry points for leverage of regulatory action. In figure 23 we show an outline of the emerging ecosystem with current players mentioned in this report and the relationships they have built so far. Similar to any new emerging field, the media and how they report to the wider public plays a strong role in shaping the image and public opinion of the technology. 3D printed food is still seen as a futuristic curiosity rather than a serious food processing technology, hence consumer expectations may be shaped by this image of the technology. It can also be seen that although cautiously, large food manufacturers are entering the 3DFP ecosystem bringing considerable experience and commitment to food production safety standards to it. The 3D printer manufacturers are mainly concept developers creating bespoke printers for specific food types investing considerable R&D to make the printing process more robust. The consumer is currently more a spectator in this ecosystem rather than an active player, however this may change rapidly as soon as more printed food types find their way to market.

Considering this ecosystem structure, concept developers seem to be the current hubs of the nascent industry by bringing all other players together either in collaborations or through sales of printers and expert advice for setting up operations. Obviously not all concept developers have the same level of influence. This may change as the ecosystem evolves and some companies grow and take on multiple roles to cover the full value chain, namely from production of food inks to sales of final printed food products as has happened already in a very limited number of cases. Also, as larger food manufacturers enter the ecosystem and build their own supply and value chains around 3DFP the role of concept developers may change or fade. Nevertheless, at this point in time they are central influencing hubs that generate a lot of the media attention that the technology gets and are in the position to impact the growth and shaping of the industry.

In order to give an overview of the likely temporal evolution of the various elements of the 3DFP ecosystem see fig 26 below.

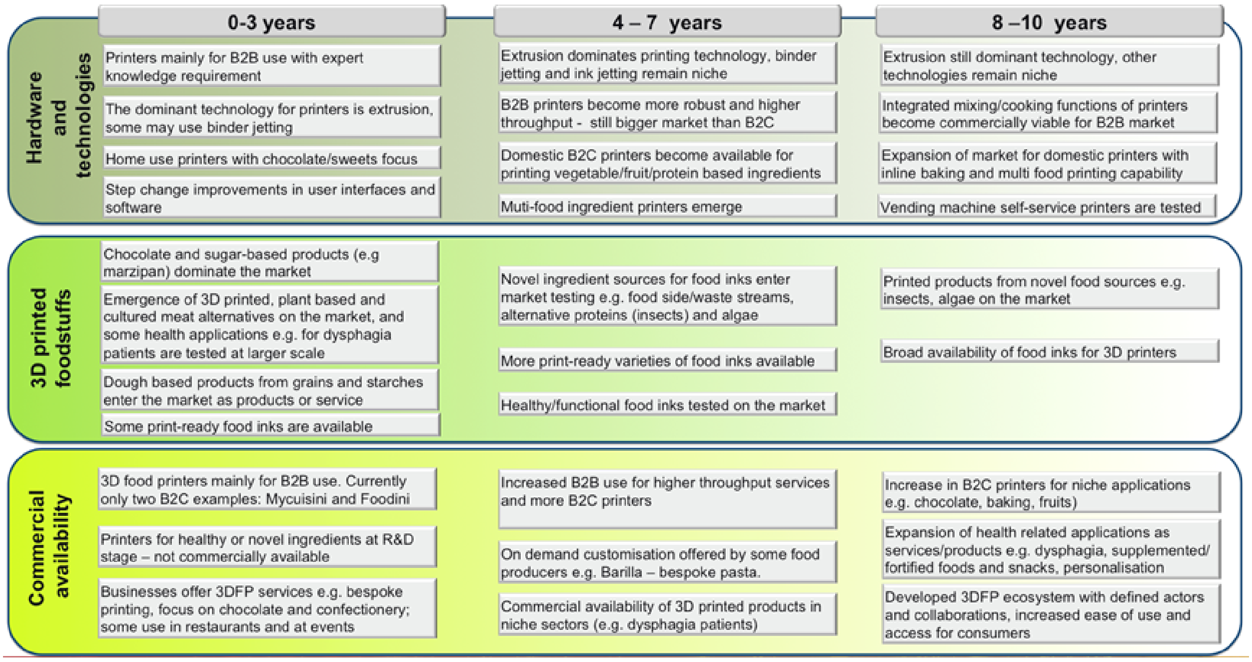

Figure 26: Indicative temporal evolution of hardware technology, formulation of foodstuffs, and commercial availability of 3DFP over the next 10 years.

In order to give a visual overview of different application areas/potential markets for 3DFP as they are indicated by current use of the technology and related R&D activities, see fig 27 below.

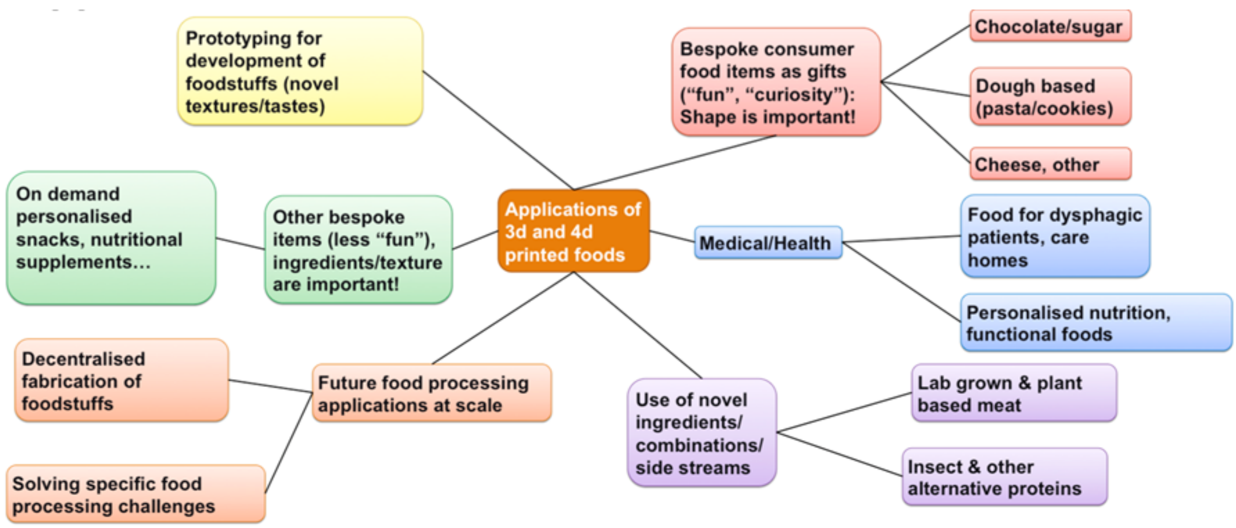

Figure 27: Overview of emerging application areas/potential markets for 3DFP.

Applications of 3D and 4D printed foods:

Prototyping for development of foodstuffs (novel textures/tastes)

Bespoke consumer food items as gift ('fun', 'curiosity' shape is important):

- Cheese, other
- Dough-based (pasta/cookies)
- Chocolate/sugar

Medical/Health

- Food for dysphagic patients, care homes
- Personalised nutrition, functional foods

Other bespoke items (less ‘fun’) ingredients/texture are important

- On demand personalised snacks, nutritional supplements

Future food processing applications at scale:

- Decentralised fabrication of foodstuffs
- Solving specific food processing challenges

Use of novel ingredients/combinations/side streams:

- Lab grown and plant based meat
- Insect and other alternative proteins

7.2.2 Short term FSA priorities (within 3 years)

Identify hubs and nodes and start engaging with the 3DFP ecosystem

- Concept developers are the hubs at the current stage of the ecosystem
- They would be key targets in the ecosystem to bring in manufacturing standards for their printers, food ink preparation processes as well as post processing steps
- Observe how the nature of the ecosystem changes as the technology develops further and the potential for scale emerges
- Set standards for labelling early in the technology evolution, as different printing technologies subject foodstuffs to different physical and chemical parameters as well as additives. This may impact the nature and nutritional properties of the end product.

Develop safety and hygiene standards for the emerging categories of printing processes:

- Printer farms
- Domestic printers
- On demand printers at local shops and supermarkets
- Small batch processors for highly personalised products
- Other emerging settings

Early prevention of potential food fraud

- Food inks for printing are complex and contain multiple ingredients which could be a target area for food fraud e.g. substituting ingredients with cheaper ones
- Decision on timing of regulation on labelling of products with regards to their novelty or degree of processing
- Early decisions of regulation and labelling may help with building consumer trust
- Engage with academia and research institutions
- Initiate more research on the impact of pre-processing, printing and post-processing on natural and nutritional properties of the food products
- Initiate research on health impacts of long term consumption of 3D printed foods as part of everyday nutrition
- Develop sustainability assessment criteria for 3DFP to enable validation of sustainability claims made by users of the technology.
- There is the potential of early regulation to help build consumer trust and support the industry in developing standards guiding developments in the manufacture of printers and development of printing processes.

7.2.3 Medium term FSA priorities (3-5 years)

- Continue research on the impact of pre-processing, printing and post-processing on natural and nutritional properties of 3D printed food
- Define standards for type and level of acceptable additives in the food ink preparations
- Establish consumer response to potential labelling requirements with regards to food ink ingredients and printing processes.

Consider assessment frameworks for the validity of claims made by 3DFP actors, and if necessary devise relevant regulation on the following claims:

- Nutritional quality
- Level of healthy/functional ingredients post processing for personalised/functional products
- Health claims and real impact on lives of specific groups such as elderly and patients with dysphagia
- Collaborate with relevant organisations, such as International Dysphagia Diet Standardization Initiative (IDDSI as they already have health impact frameworks of foods for their patient groups)
- Sustainability claims
- Water and energy use
- Real rate of conversion of food waste to real food
- Comparison with other processes with the same claim criteria in the production of healthy nutritious foods
- Continue engaging with the ecosystem players using hubs (emerging or current) as leverage points for health and safety controls.

7.2.4 Long-term FSA priorities (5 to 10+ years)

- Continue research on health impact of long-term consumption of 3D printed foods
- Establish standards of what printable foodstuff formulations (inks/pastes) are permitted. As the technical capabilities to make 3D printable food inks from many input materials will increase and it has already been speculated that there is the possibility to print "food" from chemical compounds originating from non-food material, it is important to establish definitions and inspection processes to clarify what can be printed and sold as food, and what not.

7.3 Limitations of study

We believe we have captured the most relevant areas of science and technology as well as commercial and societal trends immediately relevant to the current stage and future evolution of the 3DFP sector. 3DFP is a well-researched and studied subject with regards to technology developments, but little academic research is conducted on the commercial aspects of the field due to its early stage of market readiness. In our research we have captured the most relevant findings from the academic and grey literature available in the public domain. We have also expanded on the commercial information available by conducting a (to our knowledge) complete survey of food printers and companies, 3D food printer manufacturers, startups and larger food manufacturers entering the field. Lack of research on the commercial aspects of the sector is to some extent understandable, because despite a history of engineering research in 3DFP for over a decade, it is only recently that some viable commercial examples are emerging. The commercial and technical information provided in this report is from open sources. In-depth commercial and technical information about specific printers and products is often not available due to the short period of commercial activity of companies or is not made available to protect IP. Although we have taken care to report on most relevant trends impacting the 3DFP sector we have not attempted to quantify their impact in any form, as this would have required additional research and methods beyond the scope of this report. One major limitation for predictive analysis is the small size of the sector, and its early stage of maturity.

7.4 Proposed future research

There are a number of areas in which further in-depth research would help with expanding the evidence base for regulatory decision-making on 3DFP by:

- Gaining a better understanding of the pre-printing processes, additives used and storage and transportation requirements of food inks. These may be potentially different from other conventional food preparation processes because many food ingredients require specific proportions of additives and specific treatments to render them printable. However, these processes may change the ingredients and their nutritional profile considerably.
- Gaining a better understanding of the long-term impacts of consuming 3D printed foods on human health. This is particularly important for printed foods that are aimed at replacing main meals such as printed alternative meats or 3D printed food prepared for dysphagia patients and the elderly.
- Gaining a better understanding of the propensity of food to spoilage during the printing process. Given that the printing process is currently slow and is often carried out in ambient environments there is a possibility that food can become contaminated during the printing process. Also, the printed structures may have cavities and micro-structures that are not seen in natural food providing a suitable environment for microbial growth.
- Gaining a better understanding of the potential of the technology to impact sustainability of the food system. Currently advocates of the technology attribute sustainability benefits to 3DFP, however, these claims are not supported by evidence, and there is currently no measurement framework tested for suitability to assess 3DFP. Therefore, more in-depth research is required to better understand how the sector’s sustainability impact can be measured.