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Emerging technologies that will impact on the UK Food System

Rapid Evidence Assessment

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Abstract

Rapid technological innovation is reshaping the UK food system in many ways. FSA needs to stay abreast of these changes and develop regulatory responses to ensure novel technologies do not compromise food safety and public health. This report presents a rapid evidence assessment of the emerging technologies considered most likely to have a material impact on the UK food system and food safety over the coming decade.

Six technology fields were identified and their implications for industry, consumers, food safety and the regulatory framework explored. These fields are: Food Production and Processing (indoor farming, 3D food printing, food side and by-product use, novel non-thermal processing, and novel pesticides); Novel Sources of Protein, such as insects (for human consumption, and animal feedstock); Synthetic Biology (including lab-grown meat and proteins); Genomics Applications along the value chain (for food safety applications, and personal "nutrigenomics"); Novel Packaging (active, smart, biodegradable, edible, and reusable solutions); and, Digital Technologies in the food sector (supporting analysis, decision making and traceability).

The report identifies priority areas for regulatory engagement, and three major areas of emerging technology that are likely to have broad impact across the entire food industry. These areas are synthetic biology, novel food packaging technologies, and digital technologies. FSA will need to take a proactive approach to regulation, based on frequent monitoring and rapid feedback, to manage the challenges these technologies present, and balance increasing technological push and commercial pressures with broader human health and sustainability requirements. It is recommended FSA consider expanding in-house expertise and long-term ties with experts in relevant fields to support policymaking. Recognising the convergence of increasingly sophisticated science and technology applications, alongside wider systemic risks to the environment, human health and society, it is recommended that FSA adopt a complex systems perspective to future food safety regulation, including its wider impact on public health. Finally, the increasing pace of technological

innovation requires a more frequent and deeper scanning of the innovation landscape, and therefore faster regulatory response time frames than in the past.

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Abbreviations

Acronym	Definition
B2B	Business to business
B2C	Business to consumer
BPA	Bisphenol A
BSE	Bovine spongiform encephalopathy
CAGR	Compound annual growth rate
CPL	Cold atmospheric plasma
CRP	Controlled-release packaging
DLT	Distributed ledger technology
DNA	Deoxyribonucleic acid
EDC	Endocrine-disrupting chemicals
FFP	Former food product
GE	Genome editing
GHG	Greenhouse gases
GM	Genetically modified
GMO	Genetically modified organism
HPH	High pressure of homogenization
HPP	High hydrostatic pressure processing
IPM	Integrated pest management
IoT	Internet of things
IR	Irradiation
MBM	Meat and bone meal
NGS	Next-generation sequencing
OMF	Oscillating magnetic fields
PEF	Pulsed electric fields
PNC	Polymer nanocomposites
RFID	Radio-frequency identification
SME	Small to medium-size enterprise
UHPH	Ultra-high pressure of homogenization
UV	Ultra-violet light
WGS	Whole genome sequencing

Executive Summary

Technological innovation and adoption is reshaping the UK food system in many ways. One of the challenges for the FSA is identifying what these technologies will be, how they will change and impact on the food system, and whether they will be incremental or transformational. This rapid evidence assessment report presents an analysis of the emerging technologies considered most likely to have a material impact, either negative, or positive, on food safety and public health in the UK.

This report is a synthesis of desk research, based on thorough review of the academic and grey literature and of the food-tech start-up scene. Analysis and review was undertaken using standard rapid evidence review protocols, and qualitative analysis where necessary.

The emerging technologies were grouped into six technology fields, which, although slightly overlapping, reflect the literature and provide a clear structure for analysis and presentation. These fields are: Food Production and Processing; Novel Sources of Protein; Synthetic Biology; Genomics Applications along the value chain; Novel Packaging Technologies; and, Digital Technologies in the food sector. Many of the technologies have potential to both either reduce or enhance food safety subject to implementation. There is significant technological innovation in online distribution platforms for food that will impact on food safety for consumers, but these are the subject of a separate parallel assessment and so are specifically excluded from this report.

Food production and processing technologies

Indoor farming

Indoor farming offers the promise of year-round fresh produce, grown and harvested locally, in a controlled indoor environment that greatly reduces the risks of pests and soil-based pathogens, toxins, and climate effects.

Selected findings:

- Already commercialised, but high capital costs and high energy consumption, and a limited range of produce inhibit widespread adoption to date.

- The long-term effects of exposure to food grown in sterile, artificial environments, in permanent contact with plastics (containers/irrigation systems), is unknown.
- If not operating to strict standards, could create novel food safety risks. New regulation may be required to prevent contamination and regulate indoor pesticide use.

3D Food Printing

Offers a method of on-demand production and complex customisation of processed food products, with the ability to produce products with unique shapes, combinations of food types, and customised tastes, textures, and nutrition.

Selected findings*:*

- Already commercialised but use to-date still limited and costs are high.
- As of yet, no studies on the long-term effects of consuming 3D printed foods.
- Home use, or small shop printing presents high potential for contamination from the operating environment, and the often-considerable time it takes to print will also expose food material to continuous low to medium heat and hence can accelerate growth of pathogens.
- Risks of food adulteration and fraud (copying branded food items using different ingredients); and, the potential use of unauthorised by-products and waste streams as ingredients for printing.

Food side and by-products

This involves creating secondary products derived from primary agri-food production processes as a means to upcycle food waste, and can be a valuable source of nutrients, natural additives, bioactive compounds, and dietary fibres.

Selected findings:

- Processing may happen within global supply chains outside of the UK presenting potential regulatory oversight challenges.

- Use of waste streams presents food safety risks in collection, storage, transportation, and processing.
- A regulatory issue relates to the classification of waste streams, and how best to enable industry to actively collaborate on sharing of by-product streams.

New Non-Thermal processing technologies

A range of technologies are emerging to address the shortfalls of traditional thermal food processing (such as pasteurisation), and meet increasing consumer demand for natural, more nutritious, “fresher-like” foods. Technologies include pulsed high hydrostatic pressure processing, UV-light, irradiation, ultrasound, cold atmospheric plasma, and carbon dioxide treatment, and others.

Selected findings:

- Some of these technologies are already in use, but most have limited applications to date, and, or are still in ongoing development at lab or pilot scale.
- Further research and development is needed to better understand and resolve the potential food safety issues with these technologies, and the potential for molecular changes at the food level, carcinogens, or reduced effectivity.
- New industry standards will be needed for these emerging technologies, both to ensure safety, and to encourage broader uptake.

Novel Pesticides/Biopesticides

Over 100 chemical pesticides have been launched over the past decade or are in development, some utilising novel mechanisms of action. Novel biopesticides are also gaining attention, promising a more natural solution to pest control, made of living organisms, such as bacteria, or natural products, and essential oils. The use of nanotechnologies for optimising pesticide formulation is also an emerging area.

Selected findings:

- Biopesticides are not always as effective as their chemical counterparts, so their use may introduce susceptibility to other pests and disease.
- The longer-term impact on the soil ecosystem needs further study.

- A number of novel molecules have entered the market recently so global food trade may expose the UK to molecules not yet used in UK agriculture.
- Should be monitored and promoted as a means to a healthier food system, while staying vigilant on long term health issues for humans and allergenicity.

Novel sources of protein

Alternative sources of protein (insects, microalgae and others)

A range of protein sources are being commercialised to offer an alternative to traditional animal proteins for human consumption. The way source organisms are grown at industrial scale often involves novel production technologies and exposure of these organisms to manmade environments and novel feed sources.

Selected findings:

- The quality of feedstock (maybe organic waste streams) is a key consideration, and industry guidelines on feed, testing for pathogens, etc are needed.
- Further research is required on the treatment and processing methods and on microbial and hygienic safety, allergens, and toxicology.
- Experience with and insights into the nutritional and health effects of intensive human consumption of insects, algae, etc. are currently limited.

Novel feedstocks for livestock/aquaculture

There is significant innovation underway in feedstocks, seeking to reduce costs and improve yields. Innovations include use of alternative proteins (insects, algae, etc.), GM/GE modified crops, and food/organic waste streams as feed.

Selected findings:

- Implications for nutrition, allergenicity, and human health of novel feedstocks when used for livestock and aquaculture are poorly understood.
- Regulatory challenges around novel/GM/GE modified feedstock and waste as feedstocks, particularly when used outside the UK.

Synthetic biology / genome editing

GM/GE plants/livestock/micro-organisms for Biosynthesis

Synthetic biology covers genetic modification, and genome editing technologies used to produce higher-yielding more robust food-producing organisms, and to isolate and reassemble or optimise existing biological processes in novel ways to create nutritional molecules. Applications include genetic modification of crops and animals, and of microorganisms to efficiently produce food and bio-products for human consumption.

Selected findings:

- Techniques have been demonstrated and proven, but implementation at scale is still limited by current legislation on GMOs and consumer resistance.
- Can still have unintended effects on food, off-target mutation effects, nutritional changes, and generation of potential allergens or unknown ingredients.
- Internationally differing regulatory frameworks result in different extents of producer access to GE tools, which presents challenges for international trade and regulatory oversight.

Lab-based production (of animal proteins, meat, egg proteins, dairy)

Alternatively, referred to as cellular agriculture, applies single-cell organisms, cell culture technologies, and bioreactors for the industrial production of food and food ingredients in place of traditional agriculture and animal husbandry.

Selected findings:

- Currently still mostly in the pilot phase, expensive, and production at scale is still unproven, and there are no viable commercial products on the market to date.
- Risk of contamination in industrial-scale processes without antibiotics is high, and there may be other health considerations related to industrial scale laboratory processes (exposure to bioactive compounds, such as hormones, contact with plasticware potentially releasing chemicals harmful to humans).

- Cultured meat has less nutritional content than farmed meat, and the longer-term health implications if eaten instead of conventional meat and other processed meats need further investigation.

Genomics applications along the food value chain

Genomics use in food safety, agriculture and animal breeding

Genomics information enables a wide range of future applications in the food sector along the entire value chain, including food safety and food traceability, informing selective breeding, and, using soil microbiome knowledge to restore depleted agricultural land and oceans.

Selected findings:

- Offers the potential for accurate monitoring and control to detect food contamination and fraud, and enhance food safety and regulatory compliance.
- Successful implementation of a food safety system requires centralised, globally accessible genomics databases for pathogen and improved food source plant and animal genomes.
- System should enable rapid uploading and sharing of new data to ensure effective monitoring of foodborne pathogens as well as efficient dissemination of the use of promising new variants of food source organisms.

Genomics for personalised nutrition – “nutrigenomics”

Advances in personalised human DNA testing offer the potential for a better understanding of the gut flora, and individual human physiology, leading to personalised nutrition options, as well as tailored novel or genetically modified foods to enhance health and prevent disease.

Selected findings:

- Microbiome genomics research will help clarify causal links between antibiotics, pesticides, and other contaminants on healthy functioning of the microbiome, with potentially far-reaching consequences across the entire value chain.

- There is a risk that these tools are misused trying to sell products to consumers, based on an unscientific interpretation of genomics information that is difficult to understand for non-experts.
- From a regulatory perspective the scope of food safety will need to be expanded to encompass systemic risks to human health through novel foods and processes, particularly relating to genetically engineered food products, and possibly the burgeoning nutrition advice market.

Novel food packaging technologies

Active / intelligent / smart packaging; nanotech / biodegradable / edible films; reusable / zero packaging

Food packaging plays a key role in ensuring food safety for consumers. Innovation is seen in active packaging (offering enhanced food preservation); intelligent and smart packaging (enhancing food safety monitoring, reporting and traceability); novel nanotechnology packaging films; biodegradable and edible films; and increasing demand for reusable/returnable packaging solutions.

Selected findings:

- Novel materials, particularly involving nanotechnologies, may introduce as yet unknown allergens, toxicology, microbiological, and contamination risks.
- Shift towards reusable or zero packaging, raises food safety risks, and potential for exposure to pathogens, contamination, adulteration and food fraud.

Digital technologies in the food sector

Digital tools for analysis, decision making and traceability

Digital innovation is occurring at every stage of the value chain, and increasingly at an integrated system level. Distributed ledger technologies (such as blockchain), Internet of Things, Artificial Intelligence, digital twins, consumer-facing apps, combined with a wide array of new detection devices, smart indicators, and sensors integrated on food packaging are already being successfully implemented in the food industry, and offer unprecedented new opportunities for smart food traceability, transparency, and food safety.

Selected findings:

- The regulatory environment is complex and needs further investigation to better understand where current regulation may be inhibiting innovation and adoption, and to understand the intervention points and required actions to accelerate uptake, while ensuring system validity and integrity and food safety risks are addressed at source.
- Regulator needs to support the development of data standards, validation and scrutiny of digital technologies, and consider how independent governance might be established to support transparency and trust.
- Risks around implementation, cyber-attacks of food tracing systems, or software/hardware failures that might mislabel or misinform on millions of items.
- Roll-out at scale will be challenging due to high number of SMEs in the global food sector. FSA will need to consider how best to support uptake by SMEs.

Summary of food safety implications

Emerging Technology	Food safety risk			Enhanced food safety			Other factors	
Food production and processing technologies	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**Time frame for impact (S, M, L)**	**Regulatory action priority (1 –**
Indoor farming	No	Med	No	Med	Med	Low	M	2
3D food printing	Med	Med	High	No	No	No	M	2
Food side and by-products	Med	High	High	No	No	No	M	4
Novel non-thermal processing	Low	Med	No	No	Med	No	S-M	4
Novel pesticides/pest control	Low	Low	No	No	Med	No	S-M	4

Emerging Technology	Food safety risk			Enhanced food safety			Other factors	
Novel sources of protein	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**Time frame for impact (S, M, L)**	**Regulatory action priority (1 –**
Alternative proteins (insects, etc.) as food	Med	High	High	No	No	No	M	4
Novel feedstocks for livestock/aquaculture	Low	Med	Med	No	No	No	S	3

Emerging Technology	Food safety risk			Enhanced food safety			Other factors	
Synthetic biology/genome editing	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	Time frame for impact (S, M, L)	Regulatory action priority (1 –
GM/GE plants / livestock / micro-organisms	Med	Med	No	Med	Med	No	S-L	4
Lab-based animal meat, fats, eggs, dairy	Med	High	High	No	Med	Med	M-L	3

Emerging Technology	Food safety risk			Enhanced food safety			Other factors	
Genomics applications along the food value chain	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	Time frame for impact (S, M, L)	Regulatory action priority (1 –
Genomics for food safety/agriculture	No	No	No	Low	High	High	M-L	4
Genomics for personalised nutrition	No	No	No	High	High	No	L	2

Emerging Technology	Food safety risk			Enhanced food safety			Other factors	
Novel food packaging technologies	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	Time frame for impact (S, M, L)	Regulatory action priority (1 –
Active / intelligent / smart packaging	Low	Low	No	Low	Med	Med	S-M	4
Nanotech / biodegradable / edible films	Med	Med	No	Low	Med	No	M-L	3
Reusable / zero packaging	High	High	High	No	No	No	S-M	4

Emerging Technology	Food safety risk			Enhanced food safety			Other factors	
Digital technologies in the food sector	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**Time frame for impact (S, M, L)**	**Regulatory action priority (1 –**
Digital tools for decisions/traceability	No	No	No	High	High	High	S-M	5

High food safety risk	High improvement in food safety	S	Short-term: within 3 years
Medium food safety risk (Med)	Medium improvement in safety (Med)	M	Medium-term: 3-5 years
Low food safety risk	Low improvement in food safety	L	Longer-term: 5-10+ years
No anticipated impact	No anticipated impact		

Food safety risks: Allergens (milk, wheat, peanuts, tree nuts, fish, shellfish, soy, eggs, etc). **Contamination and toxicity** (Biological: pathogens, bacteria, viruses, etc., and unintentional or not well understood molecular changes of food product due to complexity of processing; Chemical: pesticides, antibiotics, hormone disruptors, machine oils, etc.; Physical hazards: glass, hair, etc.). **Food fraud** (Adulteration, misuse of additives, mislabelling, unauthorised GM, past use-by-date, origin and authenticity and intellectual property fraud).

Regulatory action required: Scale of 1 – 5 (low – high priority)

Recommendations

The agri-food technology sector has been evolving rapidly over the past three decades, with significant investment and innovation across the world. This has led to an increasingly dynamic and efficient innovation ecosystem of food relevant technologies. Although globally many novel technologies are currently tested locally under considerably different regulatory frameworks, this report is believed to have captured the most salient technologies immediately relevant to the UK food system and to FSA.

This evidence assessment review identified a range of emerging technologies with the potential to materially impact food safety and public health, both positively, or negatively. Some of these technologies are already implemented at scale but have not yet been fully commercialised or adopted in the UK food system. These technologies are grouped into six fields: food production and food processing; novel sources of protein; synthetic biology; genomics applications along the value chain; novel packaging technologies; and, digital technologies in the food sector.

- In the **immediate future** digital technologies may have the most notable impact on improving food safety and traceability, and this is already underway.
- In the **medium-term (3-5 years)**, the impact of production and process innovations in pesticides, non-thermal food processing, and food packaging are likely to be significant given their broad application across traditional industry. Alternative protein sources, such as insects, are gaining traction, but their impact in the UK may be greatest in animal and fish feedstock rather than direct human consumption.
- In the **medium to long-term (5-10 years)** novel technologies such as indoor farming, lab-grown meats, and food printing may have impact on the food system, but their uptake is far from certain, and they may remain small niche sectors.
- In the **longer-term** the role of genomics in informing the food system and offering personalised nutrition offers perhaps significant opportunities for change.

Some of these technologies should be monitored and promoted by FSA as a means to a healthier and more secure food system, while at the same time staying vigilant on long term health issues for humans. Food safety risks identified include exposure to novel production technologies and artificial farming environments, allergenicity, risks of food fraud, and potential misuse of synthetic biology and genomic tools.

Further research is required to better understand the longer-term food safety and health implications for most of these emerging technologies, in particular when employed in food production processes. New regulation will be required to facilitate safe uptake of these emerging technologies, to encourage investment, and provide consumer confidence for widespread acceptance and adoption.

Two primary strategic focus areas are suggested for FSA as shown in the figure below:

1. **Regulation focus:** Technologies offering benefits for the food system and consumers should not be discouraged, however, regulatory oversight is essential to ensure risks are adequately managed. In this report **two major areas of emerging technology** are identified that are of high complexity utilising a number of science and technology fields to deliver solutions and products to industry and consumers, hence impacting the food system in a highly dynamic and networked fashion. These are **Synthetic Biology** and **Novel Packaging Technologies**. These will require sophisticated policy responses to ensure the benefits of these technologies and commercial pressures are adequately balanced with the need for food safety, human and environmental health.

2. **Supporting adoption:** Technologies with the greatest potential to enhance food safety should be encouraged by FSA through appropriate regulatory changes and public engagement. Of these, **a third major group of technologies**, the **Digital Technologies**, have considerable potential to increase traceability and therefore safety of food production processes and supply chains. There are considerable implementation challenges, but the main challenge with the fast growth and adoption of these technologies lies in their systemic effects which in turn translates into systemic risks. Such risks are of an entirely different dimension and require different response models as well as time frames and scale.

		Likelihood of large-scale implementation within next decade	
		Low	High
Anticipated impact on food safety	Creates food safety risk	**Monitor development** - Indoor farming - 3D food printing - Lab-based animal meat, fats, eggs, dairy	**Regulation focus areas** - Food side and by-products - Novel non-thermal processing - Novel pesticides/pest control - Novel feedstocks for animals - Alternative proteins (insects, etc.) - Microorganisms for biosynthesis - GM/GE modified plants & livestock - Active/intelligent/smart packaging - Nanotech/biodegradable/edible films - Reusable/zero packaging
	Enhances food safety	**Monitor development** - Genomics for personalised nutrition	**Supporting adoption** - Genomics for food safety/agriculture - Digital tools for analysis, decision making and traceability

Risk-proximity matrix for emerging technologies, and recommended FSA strategic responses

This rapid evidence assessment focused on emerging technologies, but in the course of the research several **related emerging risks** were identified that FSA should consider. These include:

- Changing consumer preferences for more raw and minimally-processed foods, and a shift towards less packaging, creating a greater risk of exposure to foodborne illnesses and contaminants;

- Microbial resistance to antibiotics and pesticides threatening food production and delivery systems; climate change effects on food nutrition and availability;
- Mounting concern over plastic contamination and micro-plastics within the food system and the impact on long-term human health; mounting evidence and concern over chemicals released by plastic materials in contact with food or food input streams;
- Increasing awareness of the influence of poor nutrition and poor food choices on public health and the urgent need, not just to focus on food safety, but also food quality and nutrition.

Taking the totality of this research into consideration there emerges a strong requirement for FSA to develop a strategic approach towards policy and regulation design. To that effect regulators are increasingly required to engage with state-of-the-art technology in order to be able to support the emergence and growth of new products and services and even new industries while fulfilling their safeguarding role. This means FSA requires to move from a reactive approach to regulation and policy formation to an anticipatory approach that will require three major strategic considerations to be implemented:

Firstly, FSA to consider building effective long-term ties with experts in various fields of science and technology related to the above areas as well as some inhouse expertise in assessment and evaluation of such technologies in relation to food.

Secondly, because food at every stage of the value chain and particularly final products are often the result of convergence of increasingly sophisticated science and technology applications it is strongly advised to develop a complex systems approach to design of regulation.

Thirdly, as increasingly technology innovation in general, and so in the food sector, time frames from proof of concept to product have become much shorter. This requires not only a more frequent and deeper scanning of the innovation landscape, but also faster regulatory response time frames than in the past.

In summary it is recommended that FSA considers reimagining their role as a regulatory body and adopting a more proactive anticipatory role in supporting industry to build food safety into its fabric as novel technologies and processes increasingly replace traditional ones. This means from a regulatory perspective the scope of food safety will need to be redefined and expanded to encompass systemic risks to human health. It is recommended to adopt a systems approach to regulation using overarching conceptual frameworks such as complex dynamical systems theory to capture the realities of an increasingly dynamic, interactive and networked food system.

1 Introduction

1.1 Background

This research supports a programme of work aimed at identifying emerging challenges and opportunities for the UK food system and to ensure that the FSA is suitably prepared to meet its strategic remit. Work has previously been undertaken within the FSA looking at specific emerging technologies impacting the food system and at public risk perceptions – that work is included in the inputs to this review alongside evidence from other sources to date.

1.2 Objectives

The fast pace of technological innovation and adoption in the UK food system means that changes are likely to continue at a pace. This will change the food system in many ways, some of which we might already see coming.

We will see the impact of the fourth industrial revolution, the convergence of many new and existing technologies becoming mainstream in how we produce and consume food. Artificial intelligence, robotics, remote sensing, the internet of things, digital twins, blockchain, lab grown meat, virtual and augmented reality, driverless delivery, vertical farming, gene editing – these will all have an impact on production speeds, consumer preferences, and business behaviours. For the food industry it means it may soon be possible to ensure traceability from farm to fork in new ways, and ensure the safety and authenticity of food produced in fundamentally new ways.

The FSA's remit is to make sure that food is safe and is what it says on the label, with consumers' interests at the heart of it. To this end the FSA needs to keep up with innovation in the food industry, changing regulatory approaches to specific issues such as gene editing. Moreover, FSA needs to be ready for an increased focus on environmental regulatory changes, and be able to anticipate the needs of consumers and businesses as new ways of producing food become more mainstream.

One of the challenges for the FSA is identifying what these technologies will be, and how they will change and impact on the food system, whether this be incremental or transformational. A range of technologies are emerging or have emerged, but have not yet been fully commercialised or adopted in the UK food system. This rapid evidence assessment report is intended to highlight these technologies, identify their most likely impact on the food system, and when that impact will become material to consumers. This includes novel food production technologies that might take place outside the UK, but can have substantial downstream impact on the UK food system (e.g. novel food types, more efficient or distributed supply systems).

Identifying these technologies will allow the FSA to identify key issues that it needs to prepare for, and consider how these might affect its operations, partners and stakeholders, consumers, and the food regulatory framework.

1.3 Key research questions

This rapid assessment report seeks to address the following five research questions.

i. What are the emerging technologies likely to impact on the UK food system within the next 15 years (with indicative timescale)?

ii. What is the likely impact of the technologies on how food businesses operate e.g., premises and supply chains?

iii. What is the likely impact of the technologies on how consumers make choices about what they consume?

iv. What are the major risks and opportunities that these technologies might afford for improving food safety for consumers?

v. What are the risks and opportunities that the emerging technologies present for the regulatory framework?

1.4 Definition of food safety risks

Food safety risks can be categorised under three groups of risks (based on Gizaw, 2019). Technologies with the potential to materially influence food safety, either negatively, or positively were included in the review. Nutritional value of food and sensory properties of foods are considered a food quality issue, rather than a food safety issue, so were excluded from this analysis.

a. Allergen risk:

- 90% of all food allergenic reactions are caused by eight food types: milk, wheat, peanuts, tree nuts, fish, shellfish, soy, and eggs.

b. Contamination and toxicity risk:

- Biological: pathogens, bacteria, parasites, fungi, viruses, and unintentional or not well understood molecular changes of food product due to complexity of processing.
- Chemical: pesticides, heavy metals, antibiotics, hormone disruptors, machine oils, etc
- Physical hazards: glass, metal, hair, etc

c. Food fraud risk:

- Adulteration
- Misuse of additives
- Mislabelling
- GM foods – inclusion of unauthorised GM molecules
- Out-dated or past use-by-date
- Origin, authenticity, and intellectual property issues

1.5 Methodology

This research took the form of a rapid evidence assessment of the available academic and grey literature and a review of the agri-food tech start-up scene, including synthesis of evidence already generated within the FSA. The research process consisted of desk-based research, and analysis and review was undertaken using standard rapid evidence review protocols, and qualitative analysis where necessary, as outlined in Figure 1.

Top level scan	Systematic technology review	Detailed interrogation of evidence	Final report
Overview of emerging technology throughout food value chain to identify topics of interest.	Detailed review of emerging technologies, significance, indicative timeframes.	Detailed focus on impacts of technologies	Synthesis and interpretation and qualitative assessment
Review of FSA reports, review of reviews, agri-food tech start-up scene review.	Academic databases and grey literature	Academic databases and grey literature	Grading of evidence
	Search based on: • Alternative production and processes • Novel sources of protein • Synthetic biology • Genomics • Food packaging and circularity • Digital tools	Search based on: • Impact on how food businesses operate • Impact on how consumers choose food.	Develop recommendations
		Risks and opportunities for food safety: • Risks and opportunities for regulatory framework.	Final report preparation

Figure 1 Rapid assessment methodology

Google Scholar was used for the academic literature searches, along with Google searches for relevant grey literature, and several specific food sector start-up focused databases (e.g. Food Navigator, 2021; Forward Fooding, 2021). Where possible, we sought to identify multiple, most recent articles on each topic of interest to ensure a balanced perspective, and gave preference to more highly cited articles, or those from leading global food institutions and research groups, and government agencies.

1.5.1 Emerging technologies likely to impact the UK food system

This study first investigated technological innovations at each stage of the value chain, exploring existing innovations that have yet to be fully integrated into human food regulations, and emerging technologies likely to impact on regulations within the next 15 years.

The range of emerging technologies across the entire food value chain is vast, and while important, many of these fall outside the remit of the FSA. For the purposes of this review, the scope was constrained to emerging technologies that specifically, and materially, introduce (or reduce) the potential for consumer-facing food safety and public health risk in the UK.

1.5.2 Impact of technologies on how food businesses operate

Disruptive technologies have the potential to reshape the conventional food value-chain causing game-changing shifts in established market structures, companies and institutions (Chris, 2021). The implications of emerging technologies on how food businesses might operate were explored through a review of the academic literature and a review of emerging food technology start-ups.

1.5.3 Impact of the technologies on consumer behaviours

Research for this question draws upon existing studies undertaken by FSA, and a review of the relevant academic literature into consumer behaviour and attitudes to emerging food innovations to determine potential enablers and barriers to adoption.

1.5.4 Risks and opportunities for improving food safety

Emerging technologies have the potential to change the types of food available on the market, and the safety of our food systems. The potential risks of these new food technologies and food-adjacent technologies were explored through a review of the academic and grey literature and a review of emerging start-ups. This builds upon previous FSA risk assessment work undertaken in 2019.

1.5.5 Risks and opportunities for the regulatory framework

This question was addressed through a review of the academic and grey literature to explore how best to regulate for food safety – to ensure new food types and production processes are beneficial for public health, and to ensure consumers can have confidence in these new foods.

2 Overview of the emerging technologies

2.1 Drivers of change in the food sector

The global food system is undergoing rapid change, driven by a combination of a growing global population and shift in demographics, lifestyle changes and increasing affluence, changing diets, climate change and sustainability concerns, and emerging technologies (Doumeizel, 2019; Smith et al., 2019).

The global food system faces unprecedented challenges over the decades ahead. Despite growing continuously and becoming ever more efficient, the global food system is still failing to provide sufficient amounts and quality of nutrition to the world – 690 million people were considered undernourished in 2019, and two billion suffer food insecurity and lack of safe access to food; while at the same time rising obesity rates are a trend across the world, and diet-related diseases such as cardiovascular disease and diabetes are a rapidly growing burden on public health systems (FAO, 2020a). Against this backdrop, the global population continues to grow (forecast to reach 9bn by 2050), and rising living standards around the world are leading to a steep rise in demand for more and better-quality nutrition and particularly meat products. Moreover, climate change is threatening agricultural land and the global food production capacity and nutritional content of crops, compounding decades of soil degradation caused by over-intensive food production systems based on chemical pesticides, fertilizers and monocrops (IPCC, 2019).

The current growth trajectory is unsustainable. The food sector is placing increasing strain on the earth's biosphere and biodiversity, and is itself a major contributor to climate change as it is responsible for approximately one third of all greenhouse gas (GHG) global emissions (Crippa et al., 2021), with livestock facing particular scrutiny for being a major source of GHGs. Additionally, the current food system loses and wastes an estimated 30-50% of all produce through inefficiencies in production, distribution and particularly in consumption (UNEP, 2021).

There is a growing recognition of the need for urgent and radical change. Production yields need to increase, waste needs to reduce, environmentally and socially sustainable solutions are necessary, and consumers are increasingly demanding healthier food options and greater traceability and transparency (Smith et al., 2019).

2.2 Innovation across the food value chain

The agri-food sector is responding to these pressures with a host of technological and business model innovations. Technology push is also transforming the sector as digitization and scalable novel biotechnology methods introduce myriad innovations. Our top-level scan of the literature and agri-food tech sector identified technology innovations emerging at all stages of the food value chain from agricultural inputs through to consumption and waste/ recycling. Figure 2 presents an overview of emerging technologies, and while not exhaustive, aims to highlight the key technological trends, and illustrates the broad scope of innovations across the value chain.

These include initiatives to enhance resource productivity and efficiencies in farming and processing, novel modes of production, novel sources of food, packaging and waste solutions, and enhanced traceability throughout the value chain. Among other things, technology offers the promise of improved quality, variety, and nutritional content, innovative new delivery services and modes of purchasing food, as well as optimising personal nutrition through personalisation based on human nutritional genomics information for the future. Several over-arching areas of innovation are observed that run across the entire value chain, such as transparency and traceability innovations, reuse of by-products and waste, and innovative new consumer-facing online platforms enabling direct farm to fork access. These innovations have the potential to reshape traditional value chains entirely.

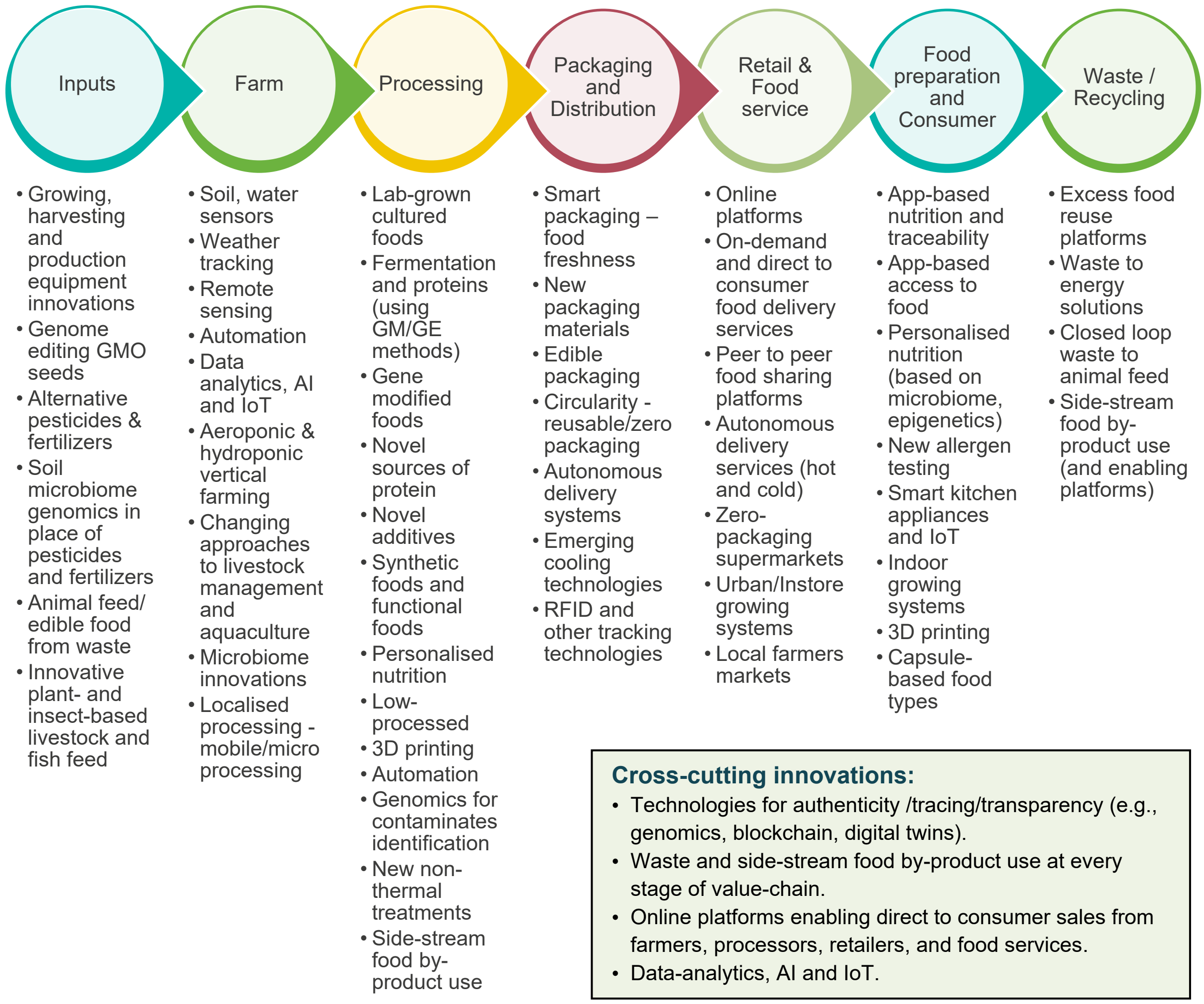
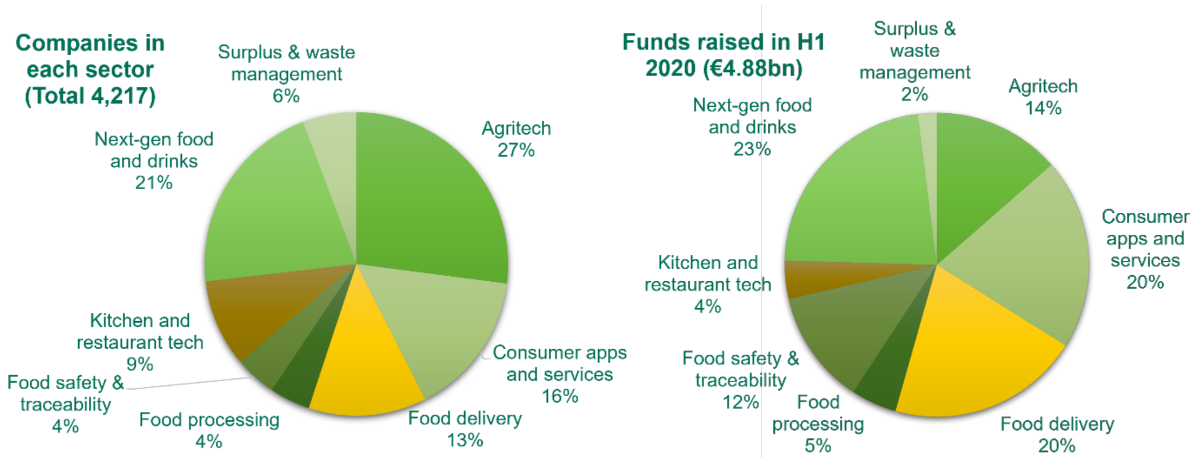


Figure 2 Overview of emerging technologies across the food value chain

2.3 Growth areas in the agri-food tech sector

The rate of innovation and investment in the food sector has expanded rapidly over the past few years. According to DigitalFoodLab (2021) global investment in the food-tech ecosystem more than doubled between 2017 and 2020 from EUR 9bn to EUR 22.3bn; and Europe registered a record-breaking level of investment of over EUR 3bn in 2019 in agri-food tech companies. Foodtech Data Navigator, that tracks start-ups in the food sector recorded approximately EUR 4.88bn invested globally across 4,217 companies in agri-food tech in H1 2020. Figure 3 presents a breakdown by category for this investment. Consumer apps and services, food delivery, and next-generation foods feature strongly in the start-up sector, raising approximately EUR 1billion each in the H1 2020 period. DigitalFoodLab (2021) present data from the European start up scene, illustrating the growing interest in Agri-tech and food sciences within Europe, as shown in Figure 4.



Source: Based on data from Forward Fooding (2020)

Figure 3 Global food-tech funding H1 2020

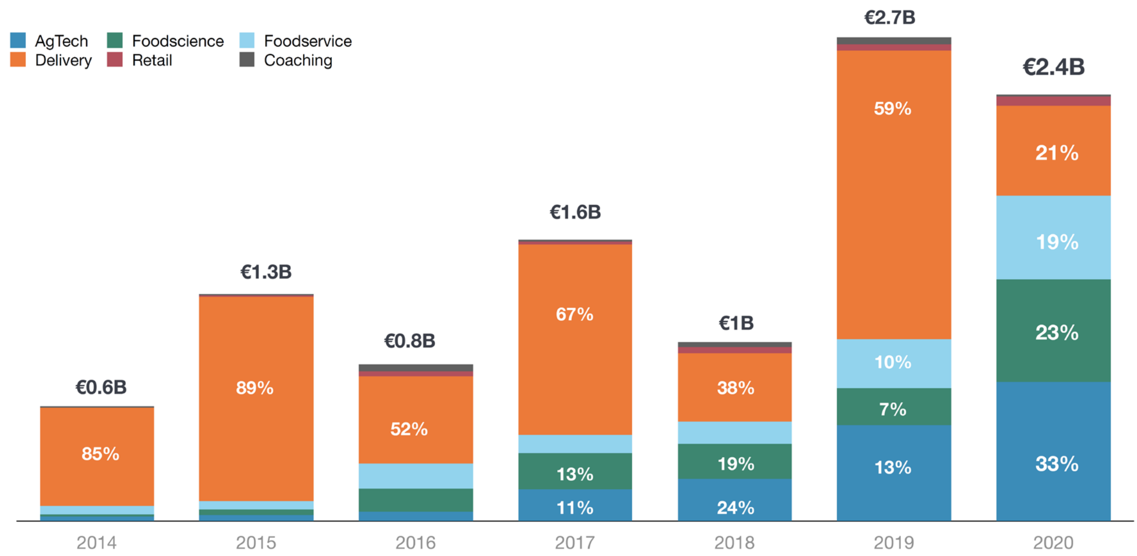


Figure 4 Investment by category (Europe)

Source: DigitalFoodLab (2021)

Forecasting what constitutes a disruptive technology for the food industry is complicated, but such technologies can cause localised change within a market or industry (i.e., first-order disruption) and cause ground-breaking changes across many cross-cutting domains (i.e., second-order disruption) over short or more extended time periods that may substantially influence societal norms (Chris, 2021).

2.4 Emerging technologies and risks to food safety and consumer perception

Many of the emerging technologies and innovations in the food industry have great promise to enhance sustainability and improve nutrition and public health, but at the same time they come with potentially significant issues around perceptions and customer acceptance, and present new food safety issues around nutrition, allergenicity, toxicity potential, and traceability that need to be addressed.

The focus of this rapid evidence assessment is emerging technologies that could have a material impact on consumer-facing food safety and public health in the UK within the next 15 years. Based on this premise, technological innovations that simply enhance efficiencies or productivity, or sustainability performance, or are considered only enablers of alternative food systems were therefore excluded. Some examples of emerging technologies considered beyond the scope of this study include distribution innovations such as autonomous vehicles, alternative farming equipment such as robotics, agricultural monitoring systems such as remote sensing, and the digital technologies that enable online food sales and distribution platforms. There is burgeoning activity in emerging online distribution platforms for food, which may impact on food safety for consumers, but these are the subject of a separate parallel assessment report and so are specifically excluded from this report.

Upon detailed review we consolidated the most salient technologies under six main technology fields of interest. Although still slightly overlapping, these fields reflect the literature, and provide a clear structure for analysis and presentation.

Emerging technology fields of relevance for FSA

Food production and food processing:

- Indoor farming and aeroponics, hydroponics
- 3D Food printing
- Food side and by-products (valorisation of waste bioresources)
- New non-thermal processing technologies

- Novel pesticides/ biopesticides

Novel sources of protein:

- Alternative sources of protein (insects, jellyfish, microalgae, etc)
- Novel feedstocks for livestock/ poultry/ aquaculture based on alternative protein sources

Synthetic biology/genome editing:

- Micro-organisms for biosynthesis of plant metabolites
- GE enhanced agricultural crops and modified functional foods
- Gene edited livestock
- Gene drives
- Lab-based production (animal proteins, meats and fats, eggs, dairy

Genomics applications along the value chain:

- Genomics information for identification food safety
- Selective breeding (animals and crops)
- Microbiome information (food safety, replacement of pesticides and fertilizers)
- Personalised nutrition based on genomics/ microbiome information
- Nutritional epigenetics tools for trait selection/ origin tracing, personalised nutrition

Novel packaging technologies:

- Active packaging with antimicrobial and other capabilities
- Intelligent and smart packaging - food safety monitoring and reporting
- Novel films – nano technologies
- Novel natural polymers, biodegrable and edible packaging
- Reusable and returnable packaging, and zero-packaging trend

Digital technologies in the food sector:

- Digital tools for analysis, decision making and traceability
- Distributed ledger technologies, AI, Internet of Things, digital twins
- New detection devices, smart indicators, and sensors, consumer-facing apps

3 Novel food production and processing

In this section we present a range of novel food production and processing technologies that have the potential to disrupt the food system and impact on food safety. Included are indoor farming; 3D food printing; food side and by-products; new non-thermal processing technologies; and novel pesticides. For each we include an assessment of the implications of the technologies on market, industry, consumers, food safety and the regulatory framework, and recommendations for FSA.

3.1 Indoor farming

Indoor farming, urban farming or vertical farming, refer to the cultivation of vegetables, fruits, herbs and grains in enclosed or semi-enclosed buildings often in cities and urban areas, using artificial heat and lighting. Applied technologies are hydroponics (growing plants in standardised aggregate substrates such as clay pebbles, stone wool or phenolic foam and water), aeroponics (growing plants on carrier scaffolds in mist) rather than soil, or aquaponics (coupling aquaculture raising aquatic animals, with hydroponics). Vertical farming refers specifically to systems that comprise multiple levels of horizontal growing surfaces enabling efficient land use compared to conventional agriculture, where one acre of vertical farming can produce as much as 10-20 acres of conventional farming (Beacham et al., 2019).

Indoor farming is not dependent on agricultural land, making the technique well suited for urban locations, located on the edge of cities, or even in the home, or supermarket. It is undertaken in a controlled environment free of most pests and pathogens, is not vulnerable to variable climate, and delivery of water, light and nutrients are optimised (Smith et al., 2019). For example, hydroponics requires only 10-15% of the water required for conventional irrigation systems in outdoor farming. A further benefit of indoor farming is year-round production making the technology suitable for harsher climates. Cassette planting of seedlings, recycling of water, automation for harvesting, and artificial intelligence to optimise the growing conditions offer the potential to enhance yields as the technology evolves.

3.2 Implications of indoor farming

3.2.1 Market

The indoor farming market in 2018 was estimated at USD 3 billion, about half of which was equipment, with Europe and Asia Pacific leading the R&D and commercialisation. The indoor farming sector is forecast to grow at a CAGR of 27.7% over the period 2019 – 2026 to reach a projected value of USD 22 billion in 2026 (Global Market Insights, 2018). While not insignificant, this is still only a tiny fraction of the USD 2 trillion global conventional agriculture. Major players in the vertical farming market include Nordic Harvest (currently Europe's largest indoor farm operation), Green Spirit Farm, Sky Greens, Aerofarms, Mirai Co. Ltd., Plantagon International, General Hydroponics, American Hydroponics, Urban Crop Solutions, among others.

3.2.2 Industry

The technology is most commonly used for strawberries, lettuce, leafy greens, and tomatoes, of which lettuce shows the greatest market potential. Many aquatic species including seaweeds are also farmed using this technique. The industry is still at an early stage, with significant R&D into growing systems to enhance performance. The technology has the potential to disrupt traditional agriculture and global supply-chains by enabling local production of fresh produce anywhere in the world. However, high initial capital costs and high energy consumption remain major barriers to widescale adoption and scale-up (Foley, 2018; Mok et al., 2020), and energy consumption at present undermines much of the environmental sustainability benefits presented for indoor farming. Moreover, the range of produce is currently limited, and as of today, it seems unlikely that indoor farming will be able to offer the full range of fruit and vegetables and grains needed for a healthy diet, and so is likely to remain a relatively niche sector. Small-scale indoor farming solutions for in-store service are already in operation, and various home-use grow systems, of varying quality, are available for consumer use.

3.2.3 Consumers

Indoor farming offers the promise of fresh greens and other produce grown and harvested locally, low levels of pesticides, and with optimised nutritional content, bringing product quality and freshness benefits. Consumer attitudes towards indoor farming are not well understood to-date. In recent surveys some viewed the produce as unnatural, less nutritious, bad-tasting, and even dangerous, while those on higher incomes levels had relatively positive attitudes toward such produce. This suggests a need for greater consumer education on the topic (Specht et al., 2019).

3.2.4 Food safety

Indoor farming in a controlled environment greatly reduces the risk of pests and soil-based pathogens and toxins accumulating in fresh produce. This offers benefits in terms of food safety. Moreover, billions of dollars are lost every year in traditional agriculture through disease, pest damage, and land and climate related effects, so indoor farming offers great potential to enhance food security (Armanda et al., 2019). However, indoor farming is at an early stage of development and there is the potential risk that, if not operating to strict standards for cleanliness, could become contaminated with pathogens and create a risk for human consumption (Smith et al., 2019). For example, water-borne pathogens can be a problem with recirculating irrigation systems, and fungicides and pesticides may still need to be used (Asaduzzaman & Asao, 2020; Wootton-Beard, 2019). The quality of the nutrient mixes for hydroponics and aquaponics is also of critical importance to the nutritional quality of the end produce. Additionally, the long-term effects of human exposure to produce grown in artificial environments, heavy use of synthetic nutrients, potential use of antifungals, and in contact with plasticware (water pipes delivering the nutrients, and the growing platforms) is unknown. Recent advances in understanding of the endocrine-disrupting chemicals (EDCs) found in many industrial materials suggest there may be risks (Alavian-Ghavanini & Rüegg, 2018). Moreover, food grown under such controlled conditions might lack some microbial activity that plays an important role in development of the human immune system and of a healthy and robust gut flora.

3.2.5 Regulation

The regulatory framework for agriculture is based on traditional farming techniques, which creates barriers for indoor farming at present. For example, EU regulation on organics demands soil, which hydroponics and aeroponics lack by definition. Being unable to use organic labelling diminishes the crop value and hence investment in the sector, and likely acts against consumer acceptance and adoption (Nelsen, 2021; Specht et al., 2019). Additionally, indoor farming is not generally eligible for the EU funding available to larger traditional agriculture, or even for local food (McEldowney, 2017; Specht et al., 2019). Building regulations may also act as a barrier to broader adoption of indoor farming as current regulations often lack provisions for large-scale indoor crop production (e.g. Simpson, 2020), and lack of compatibility with existing spatial planning policies for urban development may act against co-location with residential areas (McEldowney, 2017). New regulation is also required to ensure closer attention is paid to the choice of growing substrates, irrigation systems, tools, and the role human handling plays in preventing food from being contaminated in indoor farming environments.

This strongly indicates the need for a systems approach to regulatory design, fully considering the broad systems impact of this emerging technology area, and how best to integrate it into existing food, public health and infrastructure regulation for overall social and environmental benefit. The argument for indoor localised production in urban centres may have merit, but it is far from clear whether this is the best use of urban land, whether indoor farming offers any real sustainability benefits (given its energy and infrastructure demands), or whether indoor farming is even a desirable solution for food production in the long-term for human health. Regulators need to balance pressure from commercial interests with whether there is really a public health benefit in enabling expansion of the industry, or for example relaxing the definition of organic food, which might undermine the existing organic farming sector.

3.2.6 FSA recommendations

- Indoor farming potentially offers an opportunity to deliver improved food safety, localised food production, food security, and contributes positively on sustainability metrics related to land and water use.
- However, large-scale growing under artificial conditions presents new food safety risks that need to be explored further, and new regulation is likely required to better monitor and control emerging businesses and operations to ensure food safety.

- The technology has limitations, but if it is determined to have a beneficial role to play in the future food system then FSA will need to take a role in explaining the benefits and raising consumer awareness to facilitate adoption.
- A systems approach to policy making is required for this technology.

3.3 3D Food printing

3D food printing, or additive food manufacturing, has long been touted as a method of on-demand production and complex customisation of food products, with the ability to produce products with unique shapes, combinations of food types, and customised tastes, textures, and nutrition. Available 3D printing techniques now include extrusion-based printing, selective laser sintering, binder jetting and inkjet printing. Of these, extrusion-based printing is the most commonly used method for 3D food printing, which involves a liquid or semi-solid material being extruded through a nozzle, moving in x-, y-, and z- directions, to build up a food product layer by layer, usually followed by post-printing processing such as baking or frying (Pérez et al., 2019).

3D printing offers the potential for localised on-demand production, and is also proposed as a means for creating customised nutritional profiles of meals (Singhal et al., 2020). 3D printing is also proposed as an effective way to reduce food waste, by utilising perishable fruits and vegetables and low-value by-products such as fish and meat off-cuts that might otherwise go to waste. The technology may also be used to present novel foods such as insects and lab-grown meat in more attractive forms for consumption (Prakash et al., 2019).

Several large producers already use 3D printing technology at an industrial scale (Pereira et al., 2021), for example: Hershey's (chocolates), Barilla (pasta noodle), Ruffles (potato chips), Oreo (cookies), and Mazola (fruits and vegetables), Aleph Farms and Meatech (for printing in the production of laboratory-grown meat products), and Redefine Meat and Novameat (plant-based meat). Commercial 3D printers are available for smaller scale operations, and home use, for example, the BeeHex Robot pizza printer.

3.4 Implications of 3D Food printing

3.4.1 Market

A variety of commercial and domestic printing systems are emerging, but it is still a small niche category. The global 3D food printing market was estimated to be USD 485.5 Million in 2020, and is forecast to grow at a CAGR of 16.1% to USD 1.0 billion by 2025 (ResearchAndMarkets, 2020).

3.4.2 Industry

Despite the apparent enthusiasm around 3D printing, applications to-date are still very limited, costs are high (e.g., Foodini's 3D printer aimed at domestic users, at time of writing is USD 4,000), and printing processes are slow. Further research is required to develop food types and printing systems that are cost effective and suitable for scale-up for industrial applications. In the longer term, 3D printing may offer mass customisation, and contribute to a shift away from large centralised production towards smaller distributed localised production. However, whether this will ever really be cost effective, or even desirable is somewhat doubtful given that the current food system is built largely on huge economies of scale and production efficiencies in the industrial context, and at the other end, consumers are increasingly demanding freshly made natural foods. That said, if 3D printing were to eliminate the conventional manufacturing process for a wide variety of foods, the manufacturing system might then focus more on making simple ingredients – in powders, capsules, or other forms (Tran, 2018). As a result, a new mid-sized industry might emerge specialising on specific food segments, for example, customised curiosity food items.

3.4.3 Consumers

3D printing could deliver benefits for consumers in terms of access to foods prepared locally, new tastes, textures and nutritional content, and greater variety of customised offerings (Pereira et al., 2021). Some niche applications are already in operation. However, although research into consumer attitudes towards 3D printed foods is not extensive, studies to-date demonstrate a general resistance to new technologies for food preparation (Brunner et al., 2018). Brunner et al. (2018) observed that providing more information to consumers failed to overcome technology neophobia. Ultimately 3D printed products made from pre-processed ingredients are heavily processed foods, and current trends towards healthier minimally processed foods may work against the 3D food printing industry.

3.4.4 Food Safety

3D printers, like any other industrial or kitchen appliance, are subject to appropriate food preparation and processing standards, and use of food grade and food safe materials for food contact surfaces. However, when used in home printing machines or small shops the potential for environmental contamination of foods is high. 3D printing presents additional considerations including microbial stability in the ingredients and during the printing processes (Prakash et al., 2019), and the time it takes to print will expose food material to continuous low to medium heat and hence accelerate growth of pathogens. Moreover, as of yet, there are no studies on the long-term effects of consuming 3D printed foods (blended and powdered ingredients and altered fibre structure and other nutritional characteristics). The technology also presents specific food safety risks associated with potential adulteration of food types, potential for contamination with allergens, and there may be specific concerns related to use of by-product streams, or the potential for 3D printing to be used to hide or disguise products that are no longer fit for human consumption. Additional concerns have been raised over labelling, and intellectual property issues (Tran, 2018)

3.4.5 Regulation

Regulation will be needed on the standards of ingredients as well as validation of food printing processes and machines, for example, standard printing temperatures, cooling after printing if food remains in printer, etc.

Regulatory intervention will also be required to prevent contamination and mislabelling (inclusion of undisclosed ingredients, allergens, toxins, etc); the potential use of unauthorised by-products and waste streams as ingredients for printing; and increased potential for food fraud (e.g., the ability to print convincing copies of branded, premium products).

If 3D printing delivers on its promise of shifting to a highly distributed localised system of production, including dark kitchens, and home printing, this will create significant new challenges for monitoring and control of the food preparation sector. A shift away from large corporations towards a more fragmented market of SMEs (often with resource limitations and less rigorous food safety protocols) means policy and regulation will become harder to enforce, and it will become more difficult to balance a far more complex supply chain and marketplace with consumer needs. When combined with emerging direct-to-consumer and peer-to-peer food sales and sharing platforms (to be covered in a parallel FSA rapid assessment report) this presents a significant new food safety risk and regulatory challenge.

3.4.6 FSA recommendations

- This is an emerging technology with some potential to disrupt the current linear food value chain, from production, processing, foodservice sectors, through to home-use by consumers.
- Although rate of adoption is low and it is not an immediate concern, there is a need to start thinking about how to regulate. Regulation might be needed on the standards of ingredients, the food printing processes and machines, and use of machines in commercial contexts.
- Further study is required on the impact on consumer health of long-term consumption of 3D printed foods, because these highly processed foods may represent a systemic threat to food safety and public health.
- Although the technology has the potential to enable use of some by-products and food waste streams, there is still the risk of waste not fit for human consumption finding its way into 3D printed products. Existing regulation on waste prohibits this, and regulations will need to be reviewed to decide if and how to enable optimisation of these co-streams, while at the same time protecting consumers.

3.5 Food side and by-products

The global food system loses and wastes an estimated 30-50% of all produce, estimated at 1.3 billion tonnes per year, through inefficiencies in production, distribution and particularly in consumption (UNEP, 2021). With growing demand for food and hard constraints on expanding the food system, there is an urgent need to tackle the issue of food waste and move towards a more circular economy. One of the growing trends in this space is the use of side-products and by-products (secondary products derived from primary agri-food production processes) as a means to upcycle food waste. This is also referred to as “valorisation of bioresources”. Waste biomaterials from food production and processing have long been used for animal feed and fertilizer, but a significant majority ends up in landfill, and much less is up-cycled for valuable edible human food production (GrandViewResearch, 2020c).

Waste biomaterials have many nutritional, nutraceutical, and functional properties, and can be a valuable source of proteins, lipids, starch, micronutrients, bioactive compounds, antioxidants, texturizing agents, antimicrobials, colourants, emulsifiers, and dietary fibres (Torres-León et al., 2018). Through biotechnological processes (including bio-processing using enzymes and microorganisms; chemical processes such as alcohol precipitation; and, physical processing such as thermal and non-thermal treatments), beneficial bioactives can be extracted, and antinutritional factors present in these materials can be minimised, allowing their use as additives in a balanced food solution (Mateos-Aparicio & Matias, 2019). Functional foods, and food fortification utilising by-products offers an important strategy for tackling malnutrition and optimising health (Torres-León et al., 2018). Applications for agri-food by-product compounds have been identified from a wide range of food wastes including fruits, vegetables, grains, rice, animals, fish, and poultry (Faustino et al., 2019). Some examples of by-product use include brewer’s spent grain transformed into flour (42 million tonnes of spent grain is currently discarded annually); and gluten-free flour produced from soymilk and tofu by-products (Southey, 2019). While there are challenges, the use of by-products offers a significant opportunity to reduce waste to land-fill, improve food security, and generate new economic value for industry.

3.6 Implications of use of food side and by-products

3.6.1 Market

According to GrandViewResearch (2020), the global food waste management market size was estimated at USD 34.22 billion in 2019, and is expected to expand at a compound annual growth rate (CAGR) of 5.4% from 2020 to 2027. However, this is a fragmented sector, and we were unable to validate these figures elsewhere, or determine what market share high quality food additives created from by-product bioresources might represent. Conventional food waste management practices, based largely on landfilling, compositing, incineration, etc. are not the best use of bioresources, and regulatory pressure is now building to reduce food waste and organic waste to landfill, along with rising interest in fortified food products and demand for natural additives, which are anticipated to drive growth in this sector.

3.6.2 Industry

Maximising the use of by-products requires development of appropriate industrial processes and industrial eco-systems of partners, and possibly co-located processing facilities to optimise operations. A range of industrial pre-treatments (primarily to reduce the water content in the by-products, such as thermal drying, centrifugation and filtration, mechanical pressing), and processes/treatments for extraction (bioprocessing, chemical, and physical treatments) are already available and, or are in development and scale-up for industrial applications. Expansion of the sector will depend on cost-effectiveness and yields of these emerging processes. Strong examples of synergistic use of by-product streams with co-located processing facilities are seen in the sugar industry (e.g., British Sugar, Wissington, UK). The majority of primary processing of agri-foods is undertaken in developing nations, which creates significant opportunities for by-product use and development of fortified food products for use in these regions of the world (Torres-León et al., 2018), but there are opportunities throughout the food production and manufacturing sector. In the longer-term use of agri-food by-products may possibly lead to a reduction in the use of artificial additives, and an increase in new health food/fortified food offerings, creating a shift in certain segments of the food industry.

3.6.3 Consumers

As consumer awareness around food and health rises, there has been a growing demand for natural products, free of artificial additives. The use of agri-food by-products potentially offers consumers an alternative with the same technological effect, but free of the negative perceptions associated with synthetic additives

(Faustino et al., 2019). That said, consumer attitudes towards waste-to-food solutions may present a barrier to uptake (Aschemann-Witzel & Stangherlin, 2021)

3.6.4 Food Safety

Potentially, the use of by-products could increase food safety by reducing dependence on synthetic additives. However, due to the composition and high water content of most food waste it has high biological instability and among other things has a potentially pathogenic nature (Mateos-Aparicio & Matias, 2019). Therefore, use of any new waste streams presents potential challenges, and it will be essential to ensure they are collected, stored and transported, and processed appropriately to maintain food safety. There may be opportunities for the food industry to use learnings from the pharmaceuticals industry and how they manage high grade raw material supply chains.

3.6.5 Regulation

Extensive regulation already exists for the use of additives, and this should suffice for many food by-products, and there is a consensus that if an additive compound/molecule is already included in the list of authorised compounds, it can be used. However, where new production processes are involved in the extraction and use of by-products there may be a requirement for new evaluation to ensure their food safety (Faustino et al., 2019). Moreover, there are issues over potential fraud and use of unauthorised waste streams. This raises an important question over how to balance need for regulation at source where these by products are collected and handled and processed (possibly in developing nations co-located with primary processing plants and their by-product and side-product waste streams), or to regulate at end-product level.

3.6.6 FSA recommendations

- FSA will need to stay abreast of developments in this sector and more in-depth research is recommended to understand the scope and scale of innovations, where in the world (and under what regulation) these initiatives are being introduced, and what is novel versus proven technologies.
- The rapidly growing number of start-ups offering innovative new food products and fortified products based on by-products, like any novel foods need to be

monitored for health and nutritional concerns, and new regulation may be required on novel additives.

- FSA will need to ensure regulation is able to provide consumer protection from products originated outside the UK, possibly from regions without regulation over use of by-product and food waste streams, and decide whether this regulation should be at source, or at the end product level.
- A specific issue relates to the classification of waste streams, and how best to enable (or restrict) industry in actively collaborating on sharing of by-product streams and developing industrial symbiotic relationships.

3.7 New non-thermal processing technologies

Conventional thermal food processing technologies, such as blanching, pasteurisation, sterilisation, canning, baking, roasting and frying, involve the application of heat to a food material for a specified period of time to reduce or destroy microbial activity, enzyme activity, and to produce physical or chemical changes to meet a certain quality standard. However, thermal processing technologies are energy intensive, processing times can be lengthy, and can have a detrimental impact on the nutritional content and sensory properties of the foods (Galanakis, 2021; Z.-H. Zhang et al., 2019). Consumers are increasingly demanding products with minimal processing and with the characteristics of fresh produce, but that are still healthy and safe with long shelf-lives.

A range of non-thermal food preservation technologies are emerging to try to address the shortfalls of traditional processes, delivering processing efficiency improvements, and creating new value for manufacturers and consumers. These technologies use a variety of mechanisms for microbial inactivation of microorganisms on the surface and, or within the food product. Emerging technologies include high hydrostatic pressure processing (HPP), pulsed UV-light (UV), irradiation (IR), pulsed electric fields (PEF), oscillating magnetic fields (OMF), ultrasound (US), and cold atmospheric plasma (CPL), high pressure of homogenisation (HPH), ultra-high pressure of homogenisation (UHPH), membrane processes, and supercritical carbon dioxide treatment (Khouryieh, 2021; Wang et al., 2020; Z.-H. Zhang et al., 2019). Technologies are often used in conjunction with other processes to achieve the desired microbial inactivation and production efficiencies – for example, HPP is often combined with thermal treatment to reduce the overall processing time.

Depending on the technology, treatments may be applied pre- or post-packaging. For those processes applied post-packaging, such as HPP, this places particular mechanical requirements on the choice of packaging material. Consequently, these non-thermal processing technologies are evolving in parallel with novel packaging technologies (discussed in section 7).

By enabling products traditionally considered as perishables to be stored longer-term at room-temperature these technologies offer potential benefits for retailers and consumers, reducing premature food spoilage and food waste, and could significantly reduce transportation and storage costs, energy demands, and carbon emissions associated with cold storage and distribution cold-chains.

3.8 Implications of new non-thermal processing technologies

3.8.1 Market

According to MarketsandMarkets (2021) the non-thermal food preservation market was estimated to account for USD 1.3 bn in 2020, and is projected to grow by CAGR of 19.8% to a value of USD 3.9 bn by 2026. HPP currently dominates the non-thermal food treatments market. The market is growing rapidly driven by the commercialisation of new technologies, and the increasing demand for packaged foods and the growth in the convenience food sector such as frozen and ready-to-eat meals. North America is estimated to have the largest market share and highest growth rate.

3.8.2 Industry

Some of these technologies are already in use, but most have limited applications to date, and, or are still in ongoing development at a lab or pilot scale. Development is led by equipment manufacturers, large scale food producers, and academic and government research institutions. Cost of the technologies is often cited as a significant barrier to adoption, there are various issues around industrial safety of some of the technologies, and further work is required to address current limitations that currently hamper commercialisation at scale (Picart-Palmade et al., 2019; Priyadarshini et al., 2019). Further research is also required to determine the effectiveness of these technologies for dealing with allergens (Chizoba Ekezie et al., 2018).

3.8.3 Consumers

The technologies offer the potential for a broader range of healthier and tastier products for consumers, and may also enable alternative packaging solutions. However, consumer awareness of these technologies is currently low, and concerns over consumer acceptance (e.g. particularly of irradiated food products, which is one of the most effective processes) has been cited as a potential barrier to widespread adoption (Priyadarshini et al., 2019).

3.8.4 Food Safety

Consumer demand for convenience and “fresh-like” produce will continue to drive demand for better non-thermal technologies, but there are currently limitations in the application and effectiveness of these technologies in dealing with microbes, spores, and enzyme activity, and there are limitations on the food types to which they can be successfully applied without degrading the food. There is also limited understanding of the molecular-level effects of some of these technologies on food safety. Further research and development are needed to better understand and resolve the food safety issues and any long-term implications for human health associated with these technologies.

3.8.5 Regulation

New industry standards will need to be developed for these emerging technologies, both to ensure safety, and to encourage broader uptake. Regulation is required on at least two levels:

1. The molecular changes to the food material undergoing these processes. E.g., potential changes in nutritional content; nano particle generation; toxicity caused by molecular changes such as release of carcinogens.

2. Safety of such technologies at the appliance level in industrial, gastronomy and domestic settings. Some of these technologies introduce health and safety issues. It will be necessary to determine if small scale processing has a different effect than large scale processing, whether the technologies can be applied in batch or continuous processes, and safe levels for processing/exposure times for these treatments.

3.8.6 FSA recommendations

- A more in-depth assessment of this area of technology is recommended, particularly with regards to the potential for molecular-level changes to foods and generation of carcinogens, degradation of nutritional characteristics, and the potential for reduced efficacy relative to traditional thermal processes.
- FSA should question whether all of these new technologies are actually in the best interests for consumer food safety and public health, or whether alternative solutions should be promoted. That is, the technical ability to create “fresh-like” foods, should not detract from the provision of real fresh foods.
- Appropriate engagement in the development of the regulatory framework is required to enable industrial development and adoption as appropriate, remaining cognisant of the potential threats of these emerging technologies.
- These technologies may well be applied in production processes outside of the UK, so FSA will need to stay abreast of global developments in this area, and remain vigilant to the prospect of processed foods entering the UK food system. Regulation at source, or regulatory disclosure requirements on end products are possible options.
- FSA will need to take a lead in educating consumers and addressing consumer acceptance issues with these technologies.

3.9 Novel pesticides – biopesticides

Agricultural pests, such as insects, fungi, weeds, and bacteria undermine crop health and reduce quality and yields, presenting a significant challenge to food security. The preferred solution to this problem for the past half century has been synthetic chemical pesticides, produced by a small number of large, global agrochemical companies. However, rapid evolution and global spread of plant pathogen species that are resistant to currently used chemical pesticides, and the urgent need to reduce the negative side effects of these pesticides on the environment (particularly on pollinators) and human health, is driving a search for novel alternatives (e.g. Chaudhari et al., 2021; Jeschke, 2021).

At least 105 chemical pesticides have been launched over the past decade or are in development: 43 fungicides with various novel modes of action; 34 insecticides/acaricides, some utilising novel mechanisms of action on cell physiological pathways (e.g. Flupyradifurone and flupyrimin, exhibiting low honeybee toxicity); 6 nematicides; 21 herbicides with varied modes of action (but none commercialised with novel modes of action in nearly three decades, although products have emerged in the past two years); and 1 herbicide safener (Umetsu & Shirai, 2020). Most of these are considered safe to humans and environmentally friendly.

Some natural product origin pesticides, biopesticides, are also getting attention, promising a more natural solution to pest control, made up of living organisms or natural products, and essential oils (Chaudhari et al., 2021; Maliang et al., 2021; Martínez-Zavala et al., 2020; Veliz et al., 2017). Biopesticides can be classified into different categories, such as microbial pesticides, plant-incorporated protectants and biochemicals (Samada & Tambunan, 2020). Numerous biopesticides have been released and some now dominate the market, including Bacillus thuringiensis (Bt) which has been used for over three decades, Neem, Baculoviruses and Trichoderma (fungicide). Markets for these products include households, greenhouses, parks and organic agriculture. To optimise crop productivity, biopesticides are used in an integrated pest management (IPM) scheme, implemented in parallel with a reduction and clean-up of chemical pesticides. However, use of bioactive compounds remains rather limited because of high volatility, poor water solubility and susceptibility towards degradation (Chaudhari et al., 2021).

Advances in genomics sequencing offers the potential for development of innovative new biopesticides better targeting specific pests, with improved stability and shelf-life, release rate and effectiveness (Fenibo et al., 2020); and nano-encapsulation/nano-emulsion is also being explored as a means to improve effectivity and expand their applicability (Chaudhari et al., 2021).

The use of nanotechnologies is also an emerging area of interest, offering the potential to contribute to sustainable intensification of agricultural production. The beneficial impact of nano-fertilizer, nano-pesticide, nano growth promoters and many more on crops is reflected in higher yields, but could also positively enhance quality of food (Ashraf et al., 2021; de Oliveira, 2021). However, there are toxicity challenges and safety concerns with these products that still need to be addressed.

3.10 Implications of novel pesticides

3.10.1 Market

The global pesticides industry was estimated to be about USD 58 bn in 2019, and forecast to grow at about 3.3% CAGR (GrandViewResearch, 2020a). Although overall market growth rates are not high, the market is undergoing a significant shift, with growth in biopesticides, particularly in Western markets, in response to growing awareness of the environmental impact of traditional chemical pesticides. There are currently over 1,500 registered biopesticides with over 300 active ingredients considered to have pesticide properties. Major companies in the industry include BASF, Syngenta (Chemchina), Bayer Crop Science, Corteva, PI Industries, Cheminova, and Hansen.

3.10.2 Industry

Emerging technologies offer the promise of less harmful synthetic chemical pesticides, and a gradual reduction in dependency on chemicals, as well as growth in more organic forms of production. However, it is not without challenges – biopesticides do not currently cover the wide range of pests that chemical pesticides can address, and efficacy, stability, degradation under UV, and other issues with biopesticides remain. Novel molecules with novel modes of action at the cellular level still need to be rigorously tested for long term human health implications. Aside from a potential increase in more organic forms of agriculture, these emerging technologies are thought unlikely to greatly reshape the existing industry structure, with the large existing multinational suppliers of synthetic pesticides well positioned to remain dominant suppliers of alternative pesticides in the future.

3.10.3 Consumers

For the consumer the growth in natural product-based pesticides may enable organic products to become more commonplace, and more affordable, meaning greater choice and better health options. Consumer resistance, and uncertainty over the health implications of novel pesticides, particularly nanotechnologies, is likely to act as a barrier to broad adoption.

3.10.4 Food Safety

Novel pesticides offer the promise of benefits for human health and food safety. However, risk to human health through long-term low dose exposure to pesticides (direct exposure in agricultural workers, or as residuals in produce) can generally only be assessed over decades, except in cases of gross misuse (over-dosing, etc.). For example, recent studies have raised awareness of evidence for a possible link between pesticide use and autism spectrum disorder (Ongono et al., 2020). Moreover, biopesticides are not always as effective as their chemical counterparts, so their use may introduce susceptibility to other pests and disease, and subsequent reduction in crop yields. Transitioning from chemical pesticides to biopesticides often requires a period to allow chemical residues to decline, during which crop protection maybe compromised, with potential impacts on food safety and food security. Furthermore, novel molecules used in pest control entering produce, such as Chitinases, will need to be tested for potential allergenicity.

3.10.5 Regulation

As regulations on pesticide use have tightened the development of new synthetic chemical pesticides has declined, with some products being withdrawn entirely. Moreover, lowered chemical maximum residue levels for agricultural imports have made it increasingly necessary for growers to reduce their reliance on the use of synthetic chemical pesticides (Ndolo et al., 2019). Given that recently several novel molecules with novel modes of action in target organisms have been released on the market it is worth following approval processes in other countries and risk assessments there, as global food trade may expose the UK to novel compounds not yet used in the UK agriculture. Regulation for these new pesticides will need to consider if and how to regulate at source (e.g., at the pesticide manufacturer level, or at the growers level, very likely outside the UK), or regulate the final end-use food products to ensure they are free of chemicals or other contaminants and allergens.

3.10.6 FSA recommendations

- The area of "alternative" and biopesticides should be monitored and promoted by FSA as a means to a healthier food system, while at the same time stay vigilant on long term health issues for humans and allergenicity.
- A more in-depth assessment of this area of technology is recommended, actively questioning whether the emerging pesticides technologies, particularly nano technologies, are in the best interests of consumer food safety and public health, and of the long-term health of the environment.
- Support for research and development, and a regulatory framework that encourages the experimentation and development of new products is recommended subject to the above.
- Newer alternative pesticides start to blur the traditional lines between natural and synthetic pesticides. This presents potential challenges around the definition of organic that FSA will need to consider (simply because an alternative pesticide is natural does not necessarily mean it is good for health).
- FSA will need to stay abreast of global developments in this area and recognise the prospect of novel pesticide-treated foods entering, perhaps already, the UK food system. Regulation at source, particularly of the major producers may be one approach, or regulation of final product content will need to be developed.

4 Novel sources of protein

Meat production as a source of nutritional proteins is perceived an inefficient use of resources, with livestock having an inefficient conversion rate of crop calories to meat calories (it takes about 23 calories of crops to product one calorie of beef), using 80% of the world's arable land, and over 70% of fresh water (FAO, 2020b). Animal husbandry is one of the primary drivers of deforestation in many parts of the world, for pastoral land for raising animals, and arable land to grow crops for animal feed. Moreover, livestock, cattle particularly, generate 7% of total global GHGs and 40% of methane which traps 30 times more heat than CO_2. Future demand for meat is anticipated to double by 2050 at current rates of adoption, in particular with persistent growth in Asia, which with current meat production systems looks increasingly unsustainable.

In this section we consider novel sources of protein for human consumption that are emerging as a potential alternative to traditional animal proteins. We also explore novel feedstocks, primarily proteins, that are emerging to enable the more efficient and sustainable production of animals, poultry and fish.

4.1 Alternative proteins for human consumption

Edible insects, jellyfish, microorganisms, and edible macroalgae (kelps and seaweeds) offer an alternative to traditional animal proteins. Of these, insects are arguably the most novel, at least for Western tastes. Insects, such as crickets, black soldier fly, grasshoppers, and mealworms have high nutritional value, are high in fats and proteins, and are also a good source of vitamins and amino acids. Scientific literature on their exact nutritional content is a growing field in nutritional sciences (e.g. (Soares De Castro et al., 2018). Insects require only one sixth of the feed of cattle, and half the feed of chicken and pigs, to produce the same amount of protein. They can be grown in vertical factories that can be placed on brown-field sites, e.g. Ynsect in France is currently the largest insect factory globally (Ynsect, 2021), and require less land and water than livestock, can be fed organic waste, and their GHG and ammonia emissions are also far lower than livestock, making them a significantly more sustainable option.

The primary market for insects and other alternative proteins will be as ingredients in the food value chain. Market categories for insects include processed whole insects, animal and pet feed products, processed insect powder, insect protein bars and protein shakes, insect baked products and snacks, insect confectionaries, and insect beverages (Allied Market Research, 2019). A by-product of insect processing is chitin, and chitin-containing leftover substrates can be used as fertiliser to promote plant health (Van Huis, 2020). Moreover, insects have the largest anti-microbial peptide reservoir of all animals, so other beneficial secondary by-products may emerge.

Microalgae has been explored as a possible food source since the 1950s, and is high in essential amino acids, fatty acids, B vitamins, and other nutrients (Mok et al., 2020). Microalgae products are cultivated, often in vertical farming systems (Spalding, 2021), with organic waste as growth substrate, and are sold in Asia in the form of dried algae, and used as sources of proteins and carbohydrates. Edible jellyfish are harvested in aquaculture operations and processed through a multi-phase drying process, using mixtures of salt and alum (Bleve et al., 2019). They are mainly consumed and marketed in Southeast Asia, but, like insects and microalgae, are a novel food in Europe with no established regulatory framework for handling and processing yet.

Macroalgae, such as seaweeds are also an excellent source of protein and other important nutrients and have the benefit of being easy to cultivate and can be grown in freshwater, saltwater and wastewater environments. They offer the potential for large-scale ocean cultivation with relatively low environmental impact. Fungi are another alternative protein source that is gaining increasing attention as a low-calorie source of protein, with a texture suitable for meat and seafood substitutes. Fungi tend to require less land, energy and water to produce than most plants (Anatürk, 2021).

For much of the developed world some of these sources of proteins are considered novel food types, but they are not new to humanity, and have long been part of the diet in many cultures. However, the way source organisms are grown at industrial scale often involves novel production technologies and exposure of these organisms to manmade environments and novel feed sources.

4.2 Novel feedstocks for animal agriculture

Feed is an essential input to animal husbandry, poultry, and aquaculture sectors. The quality of feed can greatly influence the wellbeing of the animals and the quality of the end products, and can therefore have important implications for human health and food safety. For example, the outbreak of bovine spongiform encephalopathy (BSE), commonly known as mad cow disease, is thought to have been caused by cattle being fed meat-and-bone meal (MBM) from infected livestock.

One of the major challenges for animal production is the amount of protein required, typically 60-70% of livestock production costs, and even more for aquaculture (Salter & Lopez-Viso, 2021). As consumer demand for meat and fish rises rapidly it is placing increasing pressure on the supply of feedstocks. Traditional protein sources such as soybean for livestock and fishmeal from wild catch for aquaculture are becoming increasingly environmentally and economically unsustainable (Froehlich et al., 2018; Kim et al., 2019). This is driving a search for affordable, alternative sources of protein, including macroalgae (kelps, seaweeds, etc.), single-cell proteins (microalgae, bacteria, yeasts, and fungi), insect larvae, plants not edible for humans, and genetically modified crops (Cottrell et al., 2020; Pinotti et al., 2019; Turchini et al., 2019). There are challenges around digestibility and anti-nutrients with some plant-based proteins such as soy when used in aquaculture, and development is underway to address these through genetic selection and modification and heat treatments. Insects such as mealworms and soldier fly larvae, and various algae and bacteria seem to be the most promising for use as feed for poultry, pigs and fish, and various insect types are now approved as feed for aquaculture in the EU.

Insects and single-cell organisms are fed on biomass waste such as by-products of the food industry that are not suitable for human or animal consumption. As such they offer an efficient conversion of waste streams into valuable feed ingredients in a sustainable circular manner (Salter & Lopez-Viso, 2021). The quality of these waste feedstocks is an important consideration, and may have implications for animal performance and wellbeing, and potentially might have implications for human consumption, while tailored substrates could lead to the production of premium feed.

There are also opportunities to expand the use of food waste for direct use as animal feed. Waste animal tissue from the rendering industry, and inedible meats from the retail sector can be reprocessed for use as animal protein feed, and liquid whey creating in cheese making, can be dried as whey powder and used as an ingredient in feed (Kim et al., 2019). Former food products (FFPs), which are manufactured food products in compliance with regulations but no longer intended for human consumption, such as leftover bread, pasta, or damaged confectionary, can also be reprocessed for animal feed as a valuable source of energy (Pinotti et al., 2019). However, the use of FFPs and implications for gut health of animals needs further research, and is therefore restricted to date.

4.3 Implications of emerging novel sources of protein

Similar issues, benefits and limitations are seen for insects, jellyfish and microorganisms, as sources of proteins, but for the purposes of clarity, in the discussion below we focus primarily on insects. Production of proteins for human consumption and animal feed are industrially similar so we have combined our assessment of the implications here.

4.3.1 Market

There are many hundreds of start-up companies globally currently investing in research and productisation of various types of insects, particularly crickets and black solder flies (Bug Burger, 2021). Existing applications are primarily focused on aquaculture and fish feedstocks and some applications in pet foods to-date. Insect-based products are emerging for human consumption but currently are artisan offerings of curiosity products. Bug Burger (2021) highlights commercially available products such as snack bars, crisps, burgers, cookies, etc. created from insect powder. The global edible insects market is expected to reach USD 8 billion by 2030, supported by a CAGR of 24.4% during the forecast period of 2019 to 2030; or, 730,000 tonnes by 2030, CAGR of 27.8% during the forecast period. Key players operating in the global edible insects market are Kreca Ento-Food Bv (A Proti-Farm Company), Entomo Farms, Haocheng Mealworm Inc, Agriprotein, Ynsect, Deli Bugs Ltd., among others (Allied Market Research, 2019).

4.3.2 Industry

The alternative protein industry, particularly insects, represents an opportunity to disrupt the existing food system (Payne et al., 2016). However, current solutions are still small scale, technological improvements are required to industrialise production at scale, and they are highly dependent on economically viable feedstuffs (DiGiacomo & Leury, 2019). A typical factory might produce 10 tonnes per day, but to contribute meaningfully to the global food/feed system requires factories producing thousands of tonnes per day, and it is currently still a labour-intensive industry.

Insects represent a way of transforming food waste biomasses/streams into valuable feed materials, so could make a valuable contribution to circular economy (Gasco et al., 2020), but viability at scale requires availability of affordable and suitable side-streams and waste streams for feed input (Van Huis, 2020). Co-location with suitable waste streams/by-product streams could be beneficial. The quality of the waste streams used for feed is a key consideration, and industry guidelines on feed, testing for pathogens, etc still need to be developed. Insect production is expected to take a significant role in future animal and farmed-fish feedstocks, with human consumption lagging. Secondary processors of insects, creating protein powder for inclusion in new food types, and the animal feedstock industry will grow as new market segments.

4.3.3 Consumers

Consumer acceptance of insects as a human food stuff is rising (Van Huis, 2020), but there are still barriers to wide-spread adoption and scale-up of the technologies. Van Huis (2020) suggests that insects need to be processed into ingredients that can be applied for safe and appetising products; and use in processed products seems more likely than consumption of whole insects. Innovative means of marketing insects and food might include 3D food printing (Payne et al., 2016). However, Hartmann & Siegrist (2017) in a systematic review of the literature on consumer attitudes to insects find that the question remains whether insect proteins actually have the potential to gain a permanent position in the western diet, and whether they would actually be consumed as a substitute to traditional animal proteins.

Consumer acceptance of novel proteins used as animal feed is not well understood, although recent studies suggest use of insects to feed poultry, pigs and cattle is not widely accepted, while use of insects to feed fish seems more acceptable (Domingues et al., 2020).

4.3.4 Food safety

The emerging nature of this sector means there is limited experience and insight into the nutritional and health effects of intensive human consumption of insects or other novel proteins. Similarly, there is limited research to date into the long-term implications of these alternative diets on animal health (e.g. on immunological status, disease resistance), and there are uncertainties over the efficacy of these alternative diets across different life-cycle stages of the animals (Cottrell et al., 2020). Further research is also required on the treatment and processing methods and on microbial and hygienic safety and toxicology (Hartmann & Siegrist, 2017). Insects may have the potential to transmit pathogens to humans (Gałęcki & Sokół, 2019), and there are questions around allergens, for example, chitin contamination in insect protein products has implications for allergen testing to protect consumers with shellfish/crustacean allergies. Although rare this might be more common once more chitin is consumed on a regular basis (Burton & Zaccone, 2007). Additionally, the effects of using organic waste types as feedstocks for insects require further investigation to understand the implications on nutrition, taste, and toxicology.

4.3.5 Regulation

EU and UK legislation already authorises the use of proteins from seven insect species – Black Soldier Fly, Common Housefly, Yellow Mealworm, Lesser Mealworm, House Cricket, Banded Cricket, and Field Cricket – and the allowed substrates to rear insects for feed for aquaculture animals (Adopted by the European Commission on 24 May 2017). Generally, insects seem to meet animal requirements for good growth and health. However, several regulatory issues remain and use of organic wastes is currently restricted, (e.g. aquaculture waste cannot currently be used for feeding insects), so further research and new regulation is required (Gasco et al., 2020). For human consumption these products fall within the novel foods legislation in the UK so regulatory approval is required for their use. According to

DigitalFoodLab (2021) EU regulators are on the verge of approval for mealworms as a human food type.

Regulation will play an important role in addressing public concerns and increasing consumer acceptance, and the speed of new legislation will have a significant influence on the development of the sector (Payne et al., 2016). Regulators will need to look at how to legislate for the raw material inputs and feed for insects and particularly the use of organic waste to ensure safe operation of these facilities for human consumption. Regulation will also need to be developed for the operation of factories to ensure disease and pathogens are controlled, and possibly there will be concerns over animal welfare that need to be addressed (De Goede et al., 2013). Regulators will also need to look at the inclusion of these alternative proteins in processed foods as well as labelling issues.

4.3.6 FSA recommendations

- The alternative protein sector offers an opportunity to contribute positively on many sustainability metrics and deliver enhanced food security.
- The sector seems likely to expand, particularly the animal feedstock sector, and may well prove essential to meeting humanity's future demands for protein.
- A more holistic research strategy, focused on nutrient composition and ingredient complementarity and aligned with industry needs is needed to advance animal agriculture nutrition (Turchini et al., 2019).
- FSA needs to be closely involved in the development of this sector introducing regulation and guidelines to assist in changing consumers' attitudes towards the products, and creating an environment in which industry can prosper.
- This means addressing the current restrictions around novel food classification.
- New regulation will need to be developed to better control production, and in particular production inputs and use of waste streams, to ensure nutritional value and safety of food products, and animal feedstocks.

5 Synthetic biology / Genome editing

European Commission Scientific Committees have defined synthetic biology as "*the application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms*" (European Commission, 2014). Synthetic biology includes genetic modification (GM), and genome editing (GE) technologies (not to be confused with Genetic Engineering, also GE which summarises a number of older but still widely used genetic/molecular biology methods).

Historically, definitions of GM technology in agriculture have referred to the insertion of foreign genes into plant cells, referred to as transgenics, often with no control over where exactly those genes were inserted into the genome. Unlike earlier GM techniques, GE enables editing of specific DNA (deoxyribonucleic acid) sequences at highly specific locations in the genome, enabling a more targeted insertion of foreign DNA sequences, or editing (deleting/inserting) of parts of native genes, and reducing off-target effects. The DNA changes introduced through GE are often indistinguishable from those arising through natural or induced mutation processes used in traditional cross breeding (FSA, 2021; Nature, 2021).

In this section we discuss four main themes in synthetic biology: microorganisms for biosynthesis of plant metabolites; enhanced agricultural crops and functional crops; gene edited livestock; and gene drives. We follow this with a combined assessment of the implications of these technologies for industry, consumers, food safety, the regulatory framework, and recommendations for FSA. We then present a more specific analysis of the emerging application of synthetic biology for lab-grown proteins.

For the purposes of this review, we focus on the emerging field of GE technologies. The field has been enabled by the discovery of novel enzymes in bacteria that cut and repair DNA in a highly specific manner as part of their natural anti-viral defence system (the "immune system" of bacteria). These enzymes have been developed into a toolbox of standardised techniques that allow insertion, deletion, modification or replacement of genetic material with near-complete precision. Additional rapid advancements and cost reductions in DNA sequencing, bioinformatics, computational power, and a rapidly growing biotech sector supporting GE applications, to the point of "GE as a service", have helped to make the technology widely available and relatively cheap. Precision genome editing is currently based on three major enzyme classes with different modes of action, namely CRISPR/cas9 (and a growing list of other cas enzymes, such as cas 12,13, Phi, etc), ZFN (Zinc Finger Nucleases), and TALEN (Transcription Activator-Like Effector Nuclease) systems. These technologies allow insertion/deletion/manipulation of larger stretches of DNA, including large genes as well as simultaneous editing of several genes in one editing step. Prime Editing is another emerging GE technology working along similar principles, for smaller targeted changes in DNA.

The two main contributions of synthetic biology to the global food industry are in producing higher-yielding more robust food-producing organisms and in isolating and reassembling/optimising existing biological processes in novel ways to create relevant nutritional molecules. Applications include modification of crops to deliver enhanced pest and drought resistance, enhanced nutritional content, and removal of allergens or toxic compounds; production of synthetic meat and synthetic eggs from synthetic protein sources; genetic modification of microalgae to produce biomolecules useful for humans; and, for directly synthesizing nutritious substances from chemical and mineral materials (Haskell, 2020). These solutions offer the potential to improve food security, food safety, and food nutrition, while at the same time delivering environmental sustainability benefits, waste reduction, and possibly reduced carbon emissions (Goold et al., 2018).

5.1 Microorganisms for biosynthesis of plant metabolites

Plants and animals provide a plethora of high value compounds for food and medicinal applications, but their production demands arable land and water, and is subject to seasonality and climate variability, and often long generation periods. Aquatic algae provide an alternative to plants as they grow much faster and alleviate some of these limitations but growing and harvesting at scale is labour intensive and prohibitively expensive at present. Synthetic biology offers an efficient alternative to generating these needed compounds, by using a GE modified microorganism, often a type of yeast in a fermentation process, or certain bacteria and fungi, fed with plant-derived feedstocks to generate the desired metabolites. Fermentation processes have been used for millennia to create foods such as wine, beer, and yogurts, but using modified yeasts now enables the controlled production of a much wider array of complex compounds. For example, yeasts have successfully been modified to create plant metabolites such as cannabinoids, opioids, and cocoa butter compounds (Goold et al., 2018), as well as animal proteins, such as egg and milk proteins as discussed later in this report. Not only do these technologies offer a rapid and efficient means of production, but they also offer the possibility of upgrading low value by-products of the agri-food industry as input streams into fermentation processes with modified organisms (e.g., molasses from sugar production, pulp from starch production, and processing waters from breweries) creating high value proteins as feed and food ingredients (Ercili-Cura & Barth, 2021).

5.2 Enhanced agricultural crops and functional foods

Synthetic biology offers potential to deliver improved agricultural crops to enhance productivity and nutritional value. Using genetic manipulation and insights based on genomics data, agricultural geneticists can now add dozens of traits to a plant. These traits can be quite complex, such as disease and pest resistance, climate resilience such as drought tolerance, reduced environmental impact, extended growing season, production efficiency, nitrogen utilisation and fixing, and carbon fixing (FSA, 2021; Goold et al., 2018; He et al., 2020). Among other things these offer the promise of reduced needs for chemical fertilizers, and enhanced sequestration of atmospheric carbon dioxide. Modified functional foods with enhanced nutritional content, improved taste, and reduced browning (to reduce food waste) of crops have also been successfully demonstrated; for example, carotenoid-enriched functional crops, oilseed crops boosted with omega 3 fatty acids, naturally decaffeinated coffee, and raspberries with and increased shelf life (FSA, 2021; Goold et al., 2018). An array of enhanced functional crops are in the pipeline for commercial use by 2025 (FSA, 2021)

Synthetic biology also offers the potential to expand food production by making better use of non-arable land or contaminated land, through the design of plants able to tolerate non-conventional growing environments such as areas of high salinity, or plants specifically designed to deliver a bio-remedial function, breaking down toxic compounds and clearing up heavy metal contamination, etc. (Goold et al., 2018).

There are significant challenges involved, as plant genomes are highly complex, and the process of propagation, transformation and screening is time consuming and expensive, but with the advance of editing tools these barriers are reducing. There is uncertainty over acceptance of GE crops; however, GE minichromosomal technology (or Plant Artificial Chromosomes PACs) does not alter the plant's original chromosomes, but rather adds some additional genes in individual chromosome-like DNA structures into the cell, which should result in faster regulatory approval and possibly wider acceptance from consumers.

5.3 Gene edited livestock

Traditional breeding practices are time consuming, expensive, and limited by available genetic resources. Breeding cycles and generation times can be long (e.g., biennial crops), sometimes it can take more than a decade to slightly improve the percentage of lean meat in livestock, and selection experiments involving thousands of animals are often impossible. Moreover, many domesticated animal breeds have been lost over the past century reducing the genetic pool, and limiting the breeding of novel superior varieties (Ruan et al., 2017). Early genetic breeding techniques while improving on traditional techniques still faced challenges in that breeding cycles are still long, and the lack of genetic material limits what can be achieved if the desired traits cannot be found or do not exist.

Modern GE tools in combination with genomics information offer a much more efficient mechanism for selective and cross breeding, allowing precise identification and editing of the genome to enable the transfer of beneficial genes between breeds/lines, as well as enabling genes to cross the species barrier – something that is impossible with traditional selective breeding. This can be used to ensure that genetic benefits accumulated over thousands of years through selective breeding of domesticated animals and plants are retained, genes that cause defects can be removed, whilst new traits can be quickly added and propagated. GE tools allow the generation of almost all mutation types, so animals can now acquire traits that have never previously existed in natural genetic resources. GE tools have been successfully applied to a wide variety of domesticated livestock, poultry, fish, and insect strains, and improved traits have been proven feasible and valuable. Among other benefits, the technique offers the potential to enhance product quality (nutritional content, muscle and fat content, and tenderness have all been enhanced) and increase disease and pest resistance (Ruan et al., 2017). GE has also been used, for example, to adapt predatory fish to feed on vegetarian diets. Commercialisation of GE animals is underway in China and South America, but is not permitted in the EU or US at present (FSA, 2021; Van Eenennaam et al., 2019).

5.4 Gene drives

A gene drive is a type of genetic engineering technique that modifies genes so that they don't follow the typical heredity rules. Gene drives dramatically increase the likelihood that a particular set of genes will be passed on to the next generation, allowing the genes to rapidly spread through a population and override natural selection and dilution in a population through random gene rearrangements due to sexual reproduction. They have been proposed as an effective means of genetically modifying specific populations and entire species (Friedman et al., 2020). Advanced gene editing technologies are accelerating the use of gene drives, and offer the potential for example to edit sex determination, eliminating the need for male culling in the poultry sector; selection for enhanced milk production in cattle; and as a potential means of eradicating wild populations of problem pest species, and perhaps remove insect pests from ecosystems entirely (Friedman et al., 2020; Goold et al., 2018). The technique has been demonstrated effectively in controlling malaria-carrying mosquitos, but there are considerable concerns over wider use and the potential for unintended consequences on natural populations and eco-systems.

5.5 Implications of synthetic biology

5.5.1 Market

Synthetic biology and particularly GE techniques have developed rapidly over the past decade and now offer real potential to influence development in the food and agriculture sectors (FSA, 2021). The techniques have been demonstrated and proven, but implementation at scale is still limited by current legislation on GMOs and consumer resistance to the technologies. In addition, there are process bottle necks in terms of upscaling these technologies. There are signs that regulators are moving towards accepting GE in the food system, and uptake over the coming decade seems likely to accelerate (Nature, 2021). According to ReportLinker (2021), the global market for synthetic biology in agriculture and food was estimated to be USD 3.2 bn in 2020, with a steep growth forecast of 34% CAGR to reach USD 14.12 bn by 2025.

5.5.2 Industry

GE innovations in animals and plants offer to greatly enhance efficiencies and productivity in the agriculture and livestock sectors, reducing susceptibility to pests and disease and climate variation, and enhancing quality and nutrition. Dependence on synthetic chemical pesticides and fertilisers and veterinary compounds such as antibiotics could greatly reduce, while demand for sophisticated new GE organisms is expected to rise, changing the dynamics of the agri-tech inputs and production sectors in the food value chain. However, as these technologies require a high level of expertise, laboratory capacity and agricultural infrastructure, it is likely that large agri-tech incumbents will dominate the field from the outset. Currently GE technologies, particularly, Crispr/Cas9, are suffering from a complex and litigation prone IP context that allows use of these technologies for academic research purposes, but how large-scale commercial applications will be dealt with in the future is not yet clear. This might somewhat slow down upscaling, as well as spread of novel products created with these technologies.

5.5.3 Consumers

These technologies potentially offer significant benefits for consumers in terms of nutritional value, food safety and food security. However, consumer attitudes towards any forms of genetically modified foods currently represent a significant barrier to wide-spread adoption particularly in the UK and the EU. While recent studies reject the normative assumption that consumers are anti-agri-food technologies, it is recognised that significant stakeholder engagement and consumer education on the benefits and risks of GE will be required to increase acceptance (Frewer, 2017).

5.5.4 Food Safety

Current GE technologies all have potential to induce off-target mutations, and although these may not impact on the health of individual animals, they still carry a potential risk and can create obstacles for the future promotion of genome editing. GE modifications may be intended for insertion of exogeneous genes (not naturally occurring in the genome of the organism) for a specific purpose, but have unintended effects on food, off-target mutation effects, nutritional changes in the food product, and generation of potential allergens or unknown ingredients and effects on the human intestinal flora (He et al., 2020). These unintended outcomes can only be assessed once the product has been generated, or may be only discovered once it has been already on the market for a while.

5.5.5 Regulation

Regulatory approaches to GE foods are evolving across the world. Canada and the US have a product-triggered regulatory system, whereby products are assessed on a case-by-case basis, irrespective of the technology used – the US has indicated that GE crops will be exempt if they could have been created through conventional breeding strategies (Haskell, 2020), which is however difficult to prove scientifically (Van Eenennaam et al., 2019); Argentina has a regulatory system for crops able to determine whether a GE crop should be classed as GM or a conventional crop; Europe, India, Australia and New Zealand have process-triggered GM regulatory systems, and there is ongoing review over whether GE should fall under existing GMO regulations (FSA, 2021). In July 2018 the EU ruled that GE crops should be subject to stringent GMO regulations, while the UK's DEFRA is expected to rule imminently that GE should not be treated as GMO if the results could have been produced by conventional breeding (Nature, 2021). This leaves the door open to interpretation without answering fundamental questions over what constitutes a natural mutation. Differing regulatory frameworks across jurisdictions resulting in disparate breeder access to GE tools present challenges for international trade and regulatory oversight (Van Eenennaam et al., 2019).

Unlike older GM techniques, the changes in gene edited plants and animals are often footprint-free, that is, they may be indistinguishable from mutations that could (although not necessarily ever would) occur in nature. This creates significant challenges for regulators and specific challenges in registration and tracking of the creation, reproduction and consumption of these animals and food products (Ruan et al., 2017). New industry standards and regulatory framework will be needed to provide oversight of these emerging food types. Additionally, GE modifications that could theoretically occur naturally present novel challenges that are yet to be resolved around intellectual property rights and patent protections – relating to the nature of IP rights to be assigned, to whom and the context in which they should be assigned for overall socio-economic benefit (Bera, 2015).

As discussed above, high capital costs and high operating costs of GE programmes mean that this will be the arena of large corporations rather than small businesses. The financial stakes will be high and therefore powerful political lobbying is to be expected, within the UK, and from overseas governments, particularly the powerful US agriculture and food lobby. Regulators will need a clear understanding of where they stand on GE, particularly given the ambiguities in the impending legislation and the challenges going forward.

5.5.6 FSA recommendations

- An in-depth study of the implications of GE on the food system and public health is recommended. FSA might take the lead in driving this research initiative, independent of industry, to reassure the public on the use of these technologies.
- One important point of such an initiative would be to obtain expert input on how GE applied to food production might impact consumer health, in order to establish whether GE poses novel risks as compared to older GM techniques.
- There are significant regulatory challenges to be addressed and FSA will need to decide whether they want to be at the forefront of regulation or not.

- If so, FSA will need to build and resource long-term programmes and specialist knowledge in-house in order to fully understand the critical issues, and the legal and societal implications, and be an informed independent partner in shaping the future of the industry while protecting food safety and security for generations to come.

5.6 Lab-grown meat and proteins

One application of synthetic biology is the lab-based production of animal produce, such as meat, egg and dairy. This is alternatively referred to as cellular agriculture, which describes the use of single-cell organisms, cell culture technologies, and bioreactors for the industrial production of food and food ingredients in place of traditional agriculture and animal husbandry (Ercili-Cura & Barth, 2021). Cellular agricultural products are classed either as natural cellular products (proteins made naturally by unicellular organisms, plant cells and animal cells), or acellular products (including *recombinant* food proteins such as milk and egg proteins, plant proteins, food enzymes and food additives including amino acids, fatty acids and vitamins). The latter are commonly produced by using GM technologies to insert the gene for the desired protein/molecule into bacteria or yeast, which then make the protein. Subsequently only the desired protein/molecule is extracted and purified biochemically from the bacterial/yeast culture. Applications in this field have become standard in large production segments such as dairy using lab-produced enzymes for yoghurt/cheese making.

Cellular agriculture relies on one of three mechanisms:

1. The capability of single-cell organisms to convert organic or inorganic carbon atoms into proteins, carbohydrates (sugars), lipids (fats) and other nutrients.
2. Fermentation of biologically engineered microorganisms to produce high-value acellular macromolecules.
3. Lab based, or In-vitro production of multi-cellular aggregates of plant or animal origin.

The first of these mechanisms enables the creation of food molecules industrially from nothing more than air and energy. Electricity from solar panels is used to split water to generate hydrogen, which when combined via chemical reactions with carbon dioxide from the air is used together with nutrients and vitamins as a feedstock for hydrogenotrophic bacteria that produce biomass by proliferation (e.g., Solar Foods (Finland), Deep Branch (UK), and Air Protein (US)). These can then be blended with other nutrients to create more complex food ingredients.

Egg and milk proteins are currently produced using the second mechanism, through fermentation culture of genetically modified yeast (modified to create the desired protein, usually not produced naturally by yeast). The resultant proteins of interest are then chemically extracted from the yeast culture and further processed into food ingredients, by adding nutrients, plant-based sugars and fats to create a similar texture to conventional products. The resulting ingredients can for example be used to create cheeses and yogurts.

Lab-based production, also called *in-vitro* production, cellular agriculture, or cultured foods, such as meat or seafood, is produced by taking animal muscle cells from a living animal, and cultivating them in a growth medium under laboratory conditions using laboratory technologies (Choudhury et al., 2020). Under the right conditions and by adding bioactive molecules, such as hormones and growth factors, the muscle cells divide and produce new muscle fibres in a dish. These fibres can then be processed to create a ‘meat-like product’, which could be sold alongside a conventional steak or similar meat product. The technology claims to offer significant sustainability benefits in terms of arable land use, water consumption, and GHG emissions compared with conventional animal farming. Proponents of the technology suggest it has the potential to transform the food industry, and significantly impact or displace traditional animal farming and processing. However, the processes are extremely energy intensive, and a more critical analysis of the environmental footprint of large scale food growing laboratory facilities gives a less optimistic view on realistic future growth prospects of the technology (e.g. Muraille, 2019), and its potential environmental benefits (Filcak et al., 2020).

5.7 Implications of lab-grown meat and proteins

5.7.1 Market

Dolgin (2019) observes numerous start-ups and significant venture capital investment in the sector, but a lack of academic funding is holding back development of the needed scientific and engineering expertise to bring the products into the mainstream. Products are still in the laboratory phase, with no viable commercial products on the market to date. Commercialisation may still be 5 years or more away.

5.7.2 Industry

This technology has the potential to complement animal farming and global value chains, enabling localised meat and dairy production anywhere in the world. The technology is still at an early stage, requires complex machinery, is expensive, and production at scale is still unproven. Scale-up from current medical-grade lab or pilot-scale operations to industrial operations while maintaining the necessary sterile conditions to avoid contamination and food safety risks presents a significant challenge. This is especially so for the small start-ups that represent most of the activity in this sector at present. In the case of meat production, challenges include developing better cell lines and much cheaper nutrient media to feed those cells, along with scaffolding materials to help shape cultured cells into tissue (Dolgin, 2019).

5.7.3 Consumers

The biggest challenge facing the technology is likely to be consumer acceptance and adoption. Some consumers will reject the products on the basis that they are unnatural or unethical, others because the products cannot be called vegetarian or vegan, while others may reject them on the basis of taste and texture deficiencies (Choudhury et al., 2020). Recent surveys present conflicting views on consumer openness to these emerging technologies, with significant regional variations (e.g., Bryant et al., 2019; Weinrich et al., 2020), although alternative language such as ‘clean meat’ or ‘animal free meat’ rather than ‘synthetic’ or ‘lab-grown’ may help with consumer perceptions and acceptance (Bryant & Barnett, 2019). At present, alternative plant-based “meats” seem far more likely to gain consumer acceptance and have an impact on the food sector, as successful uptake of plant-based meat products (produced by Impossible Foods) by Burger King, Trader Joe’s and Walmart in the US has demonstrated.

5.7.4 Food safety

As the process is undertaken in sterile conditions, the process theoretically offers much lower risk of pathogens, allergens and toxins, and the source materials are more easily traceable. An additional proposed benefit of lab-grown meat is the potential to avoid the use of antibiotics, but at present small quantities of antibiotics are used in most instances, and the risk of contamination in industrial-scale processes without antibiotics is high. Moreover, meat cultures are currently grown on disposable plastic materials to ensure sterile growing conditions, and the effect of long-term exposure to EDCs in plastics is not well understood (Muraille, 2019). Lab grown meat has less nutritional content than farmed meat, such as no vitamin B12, and the health implications if eaten instead of conventional meat need further investigation, and a case by case risk assessment may be required due to difference in final cell composition (FSA, 2020).

5.7.5 Regulation

These products currently fall under the novel foods regulation, and there are uncertainties over regulation at present, including whether it will need to be labelled as GMO, or if it can even be labelled as meat, or beef for example. In most countries there are also no existing frameworks for regulation of the harvesting of stem cells from livestock and growing of cells as food (Choudhury et al., 2020). There is a need to decide who is the responsible regulator, including certification and monitoring of the production processes, and traceability in case of outbreak and fraud issues. These issues, until clarified, will potentially constrain interest and investment in this emerging technology.

5.7.6 FSA recommendations

- The technology certainly has high disruption potential, but significant barriers remain, and commercialisation is still some way off, and it isn’t yet clear whether it will ever become mainstream.

- Further research is required on the human health implications of these innovative new products, and FSA should investigate how this might best be funded.
- This is an area that FSA needs to monitor closely and should work with other regulators to develop a suitable regulatory framework covering all aspects of the production process.
- Current regulations act as a barrier to commercialisation, and FSA has a significant role in either enabling or hindering the technology through decisions on future regulation.
- FSA’s approach to these technologies can be expected to have significant influence on public perceptions and hence uptake of these new food products.

6 Genomics Applications along the food value chain

Genomics is the study of whole genomes of organisms. It differs from ‘classical genetics’ in that it considers an organism’s full complement of hereditary material, rather than one gene or one gene product at a time (Whole Genome Sequencing, WGS). An organism’s DNA can be translated through a method called DNA sequencing and analytical bioinformatics tools into genomic information that can be stored in and shared via large databases. The resulting data enables exact identification of an organism by its unique DNA features, analysis of the structure and function of genomes, and provide insights on its traits.

The cost of genomics technologies have decreased dramatically over the past decade while becoming significantly faster and more accurate (Next Generation Sequencing, NGS), heralding what has been referred to as a new paradigm in “precision food safety” (Kovac et al., 2017). Genomics information and analysis of food source organisms, pests, contaminants, as well as human consumers presents a wide range of future applications in the food sector along the entire value chain, including food safety, identification of food types and food origin; selective breeding; and the promise of personalized genomics-based nutrition.

In this section we discuss three themes related to agriculture and animal breeding: genomics for food safety applications; genomics for selective breeding; and genomics of microbiomes. We then discuss two themes that focus on the role of genomics in understanding human health: genomics for personalised nutrition; and epigenetic tools.

6.1 Genomics for food safety applications

Next-generation sequencing (NGS) platforms use extensive databases and technologies to give fast and accurate DNA analysis from even minimal sample amounts such as one single cell, which can be used to test food samples against known databases of genomic information. This offers the potential to identify contamination with other ingredients, pathogens and allergens, and to confirm food type and origin (Galimberti et al., 2019). Non-targeted whole genome sequencing (WGS) is another method that can be used to identify contamination by looking at all the genetic information in a sample, and identifying anomalies that might signal the presence of a new or unknown pathogen or contaminant (Jagadeesan et al., 2019; Kovac et al., 2017).

6.2 Genomics for selective breeding / trait selection

Genetic information for the use of breeding animals and crossing plants has been used since the beginning of genetic research over a hundred years ago. However, genomics data will help to optimise livestock breeding strategies (Iung et al., 2020), and enable novel trait selection strategies in plant and animal breeding (Rasmussen, 2020). Aquaculture is currently the fastest growing farmed food sector, with highly diverse species that have only recently been farmed in human culture, and where traditional breeding strategies known from land animals are not feasible. Genetic improvements through well-designed breeding programmes supported by advances in sequencing and bioinformatics have great potential to substantially improve aquaculture to help meet rising global demand for seafood (Houston et al., 2020; You et al., 2020)

Genomics for selective breeding in itself is not thought to create direct consumer-facing food safety issues, and therefore may be of secondary relevance for FSA. We include it here to complete the picture of the role of genomics, and to highlight the potential for powerful emerging breeding alternatives to more controversial genetically modified organisms to enhance food security and food nutritional value. It should be noted that regulatory issues are relevant when genomics are used to inform the creation of genetically modified or genetically edited organisms (as discussed in section 5 on Synthetic biology).

6.3 Genomics of microbiomes

Microbiomes refer to a broad range of beneficial microorganisms such as bacteria, fungi, protozoa, and viruses, characterised by their respective genomes. The human intestinal microbiome is one example, but microbiomes are found everywhere, and play a key role in healthy ecosystems, acting as natural pesticides and antibiotics to protect plants and animals. Decades of intensive farming and extensive use of pesticides and antibiotics in the food system have diminished the microbiome in many soils and oceans. A better understanding of microbiomes might enable agronomy to better protect, or even restore microbiomes previously destroyed by industrial agriculture (Doumeizel, 2019).

An understanding of the microbiome can also potentially be used to monitor food safety and provide greater traceability and transparency in global food supply chains (Weimer et al., 2016). Foods are naturally associated with a characteristic standard set of microbes, so a shift in the microbiome might signal the presence of a pathogen, a toxin, or a different ingredient. Regular sampling of the microbiome of foods against a database of known characteristics offers the potential to catch food safety issues before disease spreads, and to reduce food fraud. The technique has also been demonstrated to identify very small differences in microbiome and can pinpoint where an item originated based on its environmental biome (Galimberti et al., 2019). Further uses of microbiomes are being explored to tackle plastic waste, and to create microbiome-based biodegradable packaging solutions to replace plastic.

6.4 Implications of genomics use in agriculture and animal breeding

6.4.1 Market

Genomics information based on WGS has rapidly gained traction in the food sector over the past few years, and is anticipated to become an indispensable part of food safety across the entire food value chain in the future (Kovac et al., 2017). Microbiome-based technologies are at a much earlier stage of development and more research is required to bring these to commercialisation at scale, but in the longer term offer the potential for higher quality food, and enhanced food safety and traceability.

6.4.2 Industry

Genomics technologies offer the potential to revolutionise food safety and food traceability by providing rapid and accurate identification of contamination issues, and pinpointing disease outbreaks. However, the technology generates large amounts of data, currently needs a high level of technical expertise, and challenges, such as long time-to-result, in implementing the technology for routine industrial practice remain (Klijn et al., 2020). A guidance framework for standardised industry applications of WGS technologies is currently emerging (Baert et al., 2021). Additionally, genomics for microbiomes offers the potential for significant disruption of agronomy, replacing conventional chemical pesticides and fertilizers with a more natural alternative, and bringing with it significant health and food security benefits.

6.4.3 Consumer

Genomics-tools for food safety are generally applied in an industrial context and will be largely invisible to the consumer but will result in enhanced food safety and traceability. This will improve the consumer experience. Test sample retrieval for genomics analysis from food items poses no risk to consumers.

6.4.4 Food safety

This technology offers food producers the potential for more accurate monitoring and control to avoid contamination in the food production system, and for more accurate monitoring of foods to estimate shelf-life. The technology also offers new ways to ensure food traceability throughout the value chain to avoid food fraud.

6.4.5 Regulation

This technology has the potential to greatly improve the regulators' ability to monitor and enforce health and food safety regulatory compliance. There are legal and IP issues around DNA data access and how it can be used that regulators may need to address. Successful implementation of a food safety system based on genomics requires centralised, globally accessible databases of pathogen genomes, and a system for rapidly uploading and sharing new data, to ensure effective monitoring of foodborne pathogens across the UK and across the world (Food Safety Magazine, 2019). Genomics of microbiomes is still at an early stage and regulation will need to develop in parallel with the technology to ensure safe and effective use in food safety, and use in modifying crops, animals, soil and oceans. When used to enhance soils, regulators will need to consider the implications this might have on organic certifications, and how best to enable widespread adoption of this new technology.

Both genomics and gene editing are scientifically broad and complex with many unknowns and un-investigated fundamental science in relation to plants, animals, ecosystems and human responses to such modifications along the food chain. This ambiguity is exacerbated with the race for translating findings in these areas into applied technologies leading to commercial processes and products to satisfy commercial interests. This puts considerable pressure on regulators to build a deep understanding of these technologies, their function, potential for positive contribution as well as challenges to the ecosystem and food systems at local, national and global levels.

6.4.6 FSA recommendations

- As discussed in the previous section on synthetic biology and gene editing, it is recommended that FSA consider building and resourcing long-term programmes and in-house expertise to enable FSA to be an informed independent partner in shaping the future of the industry while protecting food safety and security for generations to come.
- FSA should seek to be actively involved in making genomics information from relevant databases accessible and make their importance understood by the food sector providing guidance on how to use this information for food safety applications. This will require transnational partnerships with food standards agencies across the world to build a global database.
- FSA will need to work with industry to pilot and develop innovative food safety and traceability solutions based on genomics, and introduce appropriate regulation to ensure widespread adoption and compliance throughout the value chain.

6.5 Genomics for personalised nutrition – "Nutrigenomics"

The recent increase in companies offering personalised genomics services at an affordable price has triggered a rapidly growing "nutrigenomics" market driven by consumers who wish to tailor their nutritional intake to their physiological and disease predispositions in order to achieve health benefits and prevent disease

(Nasir et al., 2020; Reddy et al., 2018). Within this market, genomics information on the human gut microbiome has received much attention recently from consumers. The gut microbiome is the community of symbiotic micro-organisms such as bacteria and other microbes that inhabit the human body. The microbiome has a key role in interaction with food, our metabolism, and plays an important role in immune response and protecting against foodborne disease (Kau et al., 2011). Recent research is starting to show a strong connection between the microbiome and diseases such as diabetes, obesity, mental illness/depression and cancer; for example, tests in mice have identified specific microbes that help to control obesity. Advances in personalised DNA and microbiome testing offer the ability to better understand the roles and compositions of the microbiome (Galimberti et al., 2019), and have the potential to lead to personalised nutrition, and tailored novel or genetically modified foods to enhance microbiome health and tackle disease. Examples include engineered nano-dispersed and nano-structured foods with new absorbency properties (high, selective, delayed); prebiotics (dietary fibres to boost bacteria growth); and probiotics (living bacteria) with bifidogenic properties and immune-stimulating effects to enhance health.

6.6 Epigenetics tools

Genetics plays an important role in health, but so do behaviours and environment, such as diet and physical activity. Epigenetics is the study of how your behaviours and environment can cause changes that affect the way your genes work. Epigenetic mechanisms involve specific proteins in a cell that modify DNA in a specific manner, without changing its sequence information, which then increases/decreases/turns on/off these epigenetically modified genes. These changes in gene function are mostly reversible control mechanisms, that are usually responsive to external stimuli to the organism such as temperature, food, starvation, or stress. Unlike genetic changes that permanently change your DNA sequence, epigenetic changes are reversible, but they can change how your body reads a DNA sequence resulting in health changes, and they can be hereditary over several generations in plants and some animals including humans. Nutritional epigenetics, focusing on the epigenetic effects that certain foods have on human physiology can be used by consumers for food choices in a similar manner to nutritional genomics (Tiffon, 2018). Epigenetic or

Epigenome information can also be applied to crops and animals for trait selection for enhanced performance in specific environments.

6.7 Implications of genomics technologies on personalised nutrition

6.7.1 Market

With rising awareness of the impact of food on our health the market potential for personalised nutrition is huge, and there are already businesses emerging offering personalised microbiome-based nutritional testing. The global nutrigenomics market size was valued at USD 252.20 million in 2017 and is projected to expand at a CAGR of 16.48% from 2018 to 2025. Increasing awareness among consumers along with the increased prevalence of obesity and related ailments is expected to be a key factor driving the market (Grand View Research, 2019). Epigenetic testing is still a long way off from a mass application, as epigenetics methods are still much more expensive and scientifically less proven than genomics methods. But in the same manner companies offer a complete genome analysis for USD 100, similar is expected with epigenomics in the future.

6.7.2 Industry

As the field evolves it might develop into an important influence on consumer choices well beyond current niche applications; however, more research and development are needed to bring the technology into mainstream use. Currently the sector is represented by early to mid-stage academic spin out companies that offer individual genomics information and interpretation as a service for personal decision making around health, including nutrition.

6.7.3 Consumers

Personalised nutrition based on microbiome information offers the potential to radically reshape human health and the way we eat. Given the complex science behind this information, it needs to be monitored so that companies offering genomics/microbiome analysis services to consumers, interpret and present this scientific background accurately and correctly to the public. As consumers will have generally limited knowledge around the science, and little possibilities to evaluate the information they pay for, it will be important to define what might constitute fraud in this area.

6.7.4 Food Safety

Understanding of personalised nutrition is still at an early stage. Where conventional foods are recommended as part of a diet they are unlikely to present a food safety issue, but as technologies advance and more complex engineered products emerge the risk of harm increases. Microbiome research will help to clarify the linkages between antibiotics, pesticides, and other contaminants on healthy functioning of the microbiome, which may well have far reaching consequences across the entire value chain for the food industry in the future.

6.7.5 Regulation

This is an emerging sector that will need regulation, particularly relating to engineered food products, and scientific robustness and trustworthiness of provided genomics information offered to consumers for personal decision making. This field is well advanced in the health genomics sector and relevant regulation covering that area in the UK and abroad needs to be considered.

6.7.6 FSA recommendations

- This sector has the potential to greatly reshape the way we view the food we consume.
- As knowledge about the microbiome increases, we may see a revaluation of what constitutes a healthy diet and regulation will need to stay abreast of these developments.
- The growing nutrition advice market (numerous start-up technology companies in the space) may also require regulatory intervention to ensure consumers are not put at risk or exposed to fraudulent activity.

7 Novel Food Packaging technologies

The global food system loses and wastes an estimated 30-50% of all food produce (UNEP, 2021). In the UK, approximately 4.5 million tonnes, representing 71% of all UK food waste (excluding inedible parts), occurs at the household level due to losses in preparation and food spoilage before consumption (WRAP, 2020). Food packaging is a key method for reducing food waste by providing protection from contaminants and physical damage, enabling longer shelf-lives, and providing usage information to the consumer. Additionally, the covid pandemic has raised concerns of disease transmission via food retail, highlighting the benefit of food protective packaging, and also suggesting a need for antiviral packaging to address anecdotal evidence that the virus can spread on packaging surfaces (Olaimat et al., 2020).

At the same time, there is growing awareness of the effects of single-use plastic food packaging on human health and the environment, and government policy is pushing greater recycling and reuse solutions (Growling, 2019). The demand for safe and convenient food, that consumers perceive as being more natural or fresh-like (i.e., less processed), and packed in recyclable or reusable materials is driving demand for more sophisticated solutions (Gałęcki & Sokół, 2019; Majid et al., 2018).

In this section we present an overview of emerging packaging technologies, including active packaging (technologies offering enhanced food preservation, and enabling alternative forms of non-thermal processing); intelligent packaging (providing monitoring of food products); novel nanotechnology packaging films; biodegradable and edible films; and reusable packaging. We conclude with a summary of the implications of these emerging technologies.

7.1 Active packaging

“Active” packaging involves technologies that actively interact with the food product and the packaging headspace (the space between the product and the packaging) to prolong the storage life and enhance the margin for food safety. Such packaging can be used as a substitute for thermal and other conventional food processing techniques, enable the use of novel non-thermal processing techniques (see section 3.7), and can reduce the need for additives and preservatives within the food product

(Majid et al., 2018). This is achieved through inclusion of active components within the packaging or through the characteristics of the packaging material itself, delivering antimicrobial or antioxidant actions, absorbing gases, reducing humidity, and absorbing UV energy.

Types of active packaging include antimicrobial polymers, antioxidant compounds that stabilise oxygen sensitive food (often essential oils and other natural extracts), moisture scavengers (inorganic metals or salts), carbon dioxide emitters, and active releasing agents, all of which help to combat food spoilage. A type of active packaging is Controlled-Release Packaging (CRP) which releases an active compound onto the food product over a period of time, in order to prolong the shelf-life of the product (Vasile & Baican, 2021).

This is an area of continuous innovation, and in recent years there has been effort to improve antimicrobial performance while delivering greater environmental benefits using renewable and biodegradable substances (Becerril et al., 2020). More effective bioactive antimicrobial compounds of natural origin, such as bacteriocins, bacteriophages and essential oils, are replacing synthetic compounds. Volatility and the ease of diffusion within polymeric matrices of these bioactive compounds is still an ongoing challenge (Beltrán Sanahuja & Valdés García, 2021). However, new enzyme encapsulation and enzyme immobilization technologies in combination with novel protective films made of natural molecules, such as polysaccharides and proteins, are evolving to reduce degradation and volatilisation of antimicrobial compounds and to facilitate a more controlled release and sustained antimicrobial action (Becerril et al., 2020; Majid et al., 2018; Nogueira et al., 2020).

7.2 Intelligent and smart packaging

"Intelligent" packaging uses technologies (chemical/biochemical/electrochemical) to monitor the food product and report on the product condition and history on a simple readout, providing information on the food product quality, freshness and safety. Active packaging discussed above takes some action, while intelligent packaging senses and shares information. Used together these are often referred to as "smart" packaging (Drago et al., 2020).

Intelligent packaging involves sensors within the packaging to monitor the food itself, and external sensors to monitor the external environment, which when combined with readout technologies and other labelling technologies such as barcoding, RFID (radio frequency identification) can provide detailed monitoring and reporting throughout the product life cycle and across the supply chain. Technologies include an array of chemical and digital sensors for signalling gas leakage, ripeness regulators and indicators for fruit, time-temperature monitors, bio probes, radio frequency indicators and toxin indicators (Alam et al., 2021; Majid et al., 2018). An emerging topic building on these technologies are intelligent supply chains that offer the prospect of being able to rapidly pinpoint problem areas anywhere within distribution networks. Smart packaging can also include self-heating (using exothermic reactions), and self-cooling technologies (inducing evaporative cooling) to regulate temperature.

Most of the sensors used to-date are non-renewable and non-biodegradable synthetic materials that are incompatible with sustainability objectives. Hence, interest is growing in the use of biosensors based on bioactive natural extracts that might be used in conjunction with biopolymers to deliver intelligent and smart functionality. Bioactive extracts, such as anthocyanins have been demonstrated (that can be obtained from food by-product processing, as discussed in section 3.5), but there are still limitations that need to be overcome for broader commercialisation (Rodrigues et al., 2021).

7.3 Novel nanotechnology packaging films

Innovation is ongoing in enhanced functional barrier films that ensure active substances do not migrate into the food from food-contact materials; and innovative new high chemical barrier materials that prevent the adsorption, desorption and diffusion of gases and liquids into food products (Han et al., 2018; Majid et al., 2018). Nanomaterials, nanofibers, and nanocomposites are a focus of innovation for their potential to provide enhanced water and oxygen barrier properties, mechanical properties (stronger, more heat-resistant, and light weight, thereby reducing material requirements and transportation costs), antimicrobial activity, light-blocking properties, and inclusion of active and smart packaging functionality.

Nanotechnologies are of particular interest for use with emerging biodegradable biopolymers to enhance their otherwise limited mechanical and barrier properties, and polymer nanocomposites (PNCs) offer a potential replacement for complex multi-layered polymer structures (Sarfraz et al., 2020).

Some examples of nanotechnology include: nano-clay particles used to reduce permeability to oxygen, CO2 and moisture to protect fresh meats; and, blending of nanocomposites and oxygen scavengers in plastic drinks bottles to reduce oxidation problems with soft drinks (Majid et al., 2018). Nanotechnology applications have been demonstrated in the form of nano-sensors for detection of chemicals, bacteria, viruses, allergens, pathogens, and toxins in foods, such as E. coli and salmonella. Also, nanocomponents integrated with RFID chips are capable of detecting pathogens and moisture and temperature content, and synthetic DNA barcodes that fluoresce under ultraviolet light have been devised to monitor pathogens, and colour changing films have been developed that change colour to indicate changes in food condition (Majid et al., 2018). Future advances in nanotechnology packaging are anticipated to include stimuli-responsive polymer materials that regulate the release of molecules in response to external stimuli to enhance food preservation (Rodrigues et al., 2021).

Nanotechnology innovation is burgeoning, but in food applications there are concerns over toxicity and the migration of nanoparticles from packaging to food and into the human blood stream, and risk assessments to-date are unclear (Primožič et al., 2021). Until additional data from clinical trials is available the use of nanomaterials in the food packaging sector will remain marginal.

7.4 Biodegradable and edible films

Concern over the environmental burden of traditional petrochemical polymer-based packaging is increasing across the food sector, driving significant efforts for new solutions. Biodegradable, natural polymers, and edible packaging derived from plants, animals, and microbes are an important part of the future solution to replace chemical-based polymers (Verma et al., 2021; Yildirim & Röcker, 2021).

Biodegradable materials can be made either from petrochemical-based polymers with novel additives to enable biological breakdown, or bioplastics made from organic materials. New solutions are being developed from biopolymers such as proteins (whey proteins, wheat, corn and soy proteins, gelatin), lipid derivatives (waxes, acetylated triglycerides) and carbohydrates (starch, cellulose and its derivatives, carrageenan, pectin, chitosan, alginates) from plant, seaweed and algae, vegetable, or animal origins (Kontominas, 2020; Majid et al., 2018). For example, technologies are being developed to make composite packaging materials using grain shell fibres, and technologies for making edible meat product packaging including flavoured collagen films.

Edible coatings and films are of particular interest as a means to reduce plastic waste, using technologies that apply a protective coating (e.g. for fruit and vegetables) providing a barrier to contaminants, gases and moisture, and regulating the release of food additives and nutrients, or as edible containers (Trajkovska Petkoska et al., 2021). Examples have already been commercialised such as Apeel (US), who claim that by slowing spoilage-causing water loss and oxidation, their plant-based odourless, tasteless protective films "*keep produce fresh twice as long*" (Apeel, 2021). While edible packaging is unlikely to replace all traditional packaging, it could provide additional functionalities. Edible films can be enriched with natural additives, bioactive compounds (phenolic compounds, carotenoids, vitamins, among others), and probiotic components, to deliver antimicrobial and antioxidant performance, and improve colour and taste (Díaz-Montes & Castro-Muñoz, 2021).

The use of bioactive films to allow controlled release of bioactive compounds to the food surface to increase shelf-life, stability and food safety also looks promising, although to-date the mechanisms involved are not fully understood (Nogueira et al., 2020).

While these technologies are of great interest from a sustainability perspective, there are some significant practical challenges over production processes, mechanical and barrier performance, and interaction with thermal and non-thermal technologies which if used incorrectly can weaken films (Beikzadeh et al., 2020; Verma et al., 2021). In order to overcome these limitations nanoparticles and bioactive substances are often added, but these then reduce biodegradability. Moreover, composting or recycling of biodegradable materials is not currently catered for within existing waste processing in most countries, limiting their benefits (Nilsen-Nygaard et al., 2021).

Although biodegradable materials could already replace conventional packaging in many situations, they are currently still generally only produced on a laboratory scale, costs are high, and difficulties in standardising film properties, and post-use processing need to be resolved before production can proceed to scale (Nogueira et al., 2020).

7.5 Reusable and zero packaging

Technology is often presented as the panacea to everything, but in the case of food packaging there is a fundamental problem of finding a balance between use of technology and the reduction of waste, material and chemical use in packaging. Most of the technologies discussed above further the problem of technology devised for the sake of technology and a linear solution to a spot problem, rather than a systems approach to sustainability, human health and food safety. Even the recycling solutions are not a perfect answer to these problems.

Other approaches seek to reduce the technological content and reduce the use of disposable single-use packaging and complex materials, and introduce a more circular approach to packaging. This may be either through reusable packaging or eliminating packaging entirely. Reusable packaging types include: refillable by bulk dispenser (using customers' or brands' refillable packaging in-store); refillable parent packaging (light-weight refill packaging, maybe concentrate); returnable packaging (customers return it for cleaning and refilling, usually combined with a deposit scheme); and reusable transit packaging (Coelho et al., 2020). Refillable by bulk, and returnable packaging is gaining traction in the food sector, with examples in beverages, perishables, and take-away containers. Zero-packaging supermarkets are emerging offering a wide array of food products and produce, with consumers bringing their own containers and bags to fill in store.

These are hardly novel concepts, and before the advent of plastic they were widespread, and indeed are commonplace in many parts of the developing world today. However, they lack the convenience consumers have come to expect of single-use packaging, and lack the protective qualities, extended shelf-lives, and traceability offered by sophisticated packaging solutions described above. Existing packaging solutions help prevent cross-contamination of food products, and a ban on, or reduced access to them, in the absence of changes in retailer and consumer practices, may lead to greater persistence and circulation of foodborne pathogens within the supply chain, and increased risks of illness. However, food safety issues related to bulk selling of food could be addressed with other novel technologies.

7.6 Implications of emerging packaging technologies

7.6.1 Market

The global food packaging industry is estimated to be about USD 450 bn (e.g. GrandViewResearch, 2020b) including all packaging types, with roughly a quarter of the market each for bakery and confectionary; dairy products; and meat and seafood. Market growth is driven by many factors including increasing demands for convenience and changing lifestyles. Innovation in the sector is anticipated to continue as pressures intensify to improve food quality, reduce food waste, and reduce plastic waste. Nanotechnologies, smart packaging technologies, and biopolymers, and their convergence seem the most relevant, but there is a strong technology push driving the industry, which might not necessarily be beneficial in the long-term for the environment and society. At the same time, the push towards reusable/returnable and zero packaging, while small at present, is a growing trend. Given the various levels of market readiness of the technologies presented here, it currently seems unclear whether a robust dominant technology with a reach comparable to petrochemical-based plastics will emerge any time soon. In addition, many of the novel packaging technologies, while feasible and tested, still need to stand the test of industrial upscaling, show robustness across global markets, and prove commercially viable.

7.6.2 Industry

Emerging UK regulation and tax on single-use packaging with less than 30% recycled content, combined with changes to the extended producer responsibility legislation (to recover 100% of costs for handling waste packaging), should drive a greater shift towards use of recyclable materials across the industry, and generate greater interest in reusable/returnable packaging (although not necessarily compostable or biodegradable or edible packaging). Innovation in the manufacturing processes for these materials, and in end-of-life recycling systems will be key. A shift towards reusable packaging at the retail and manufacturing level, combined with the growth in zero-packaging stores and broader refilling solutions may start to reshape certain parts of the food retail sector. New entrants are emerging delivering zero-packaging and reusable food packaging solutions, such as Loop, and other start-ups. Major grocers and FMCG companies are also actively engaging with the concept.

7.6.3 Consumers

Packaging plays an important role in the consumer experience, providing containment and protection for the food product, convenience, communication, and in influencing food choice. Novel packaging solutions offer the promise of greater access to less-processed, fresh-like products, and, or the option of reduced disposable packaging. Studies have found consumers generally have little awareness of active and smart packaging and may be put off by novel packaging that stimulates their food/technology neophobia. Those with awareness of newer technologies perceived benefits in improving food safety and quality, but expressed scepticism over additional costs, health risks and whether it would work as advertised (Young et al., 2020). Awareness of the environmental impact of packaging is rising and consumers seem increasingly interested in reusable or biodegradable packaging, but the options are limited at present.

7.6.4 Food safety

The emerging technologies in active packaging, smart packaging, and nanotechnology offer the promise of enhanced food quality, food safety, and traceability, and far more accurate monitoring for deterioration and spoilage. These are important benefits for public health and for tackling food waste. However, use of these materials may introduce new food safety issues. Hazardous chemicals, such as endocrine disrupters, carcinogens, or substances that bioaccumulate, collectively referred to as “chemicals of concern”, can transfer from food-adjacent packaging into food, together with other unknown or toxicologically uncharacterized chemicals (Bansal & Gupta, 2020; Muncke, 2021). The long-term effects of these chemicals are still poorly understood. Moreover, novel materials, particularly nanotechnologies, may introduce as-yet unknown allergens, toxicology, microbiological, and contamination risks. Specific concerns include the migration of active and smart substances, accidental leakage of active components from a sachet, and human ingestion of active and smart substances (Han et al., 2018).

Many of the alternative biopolymers available today have reduced barrier or mechanical properties compared to traditional plastics, increasing the potential risk of exposure to contamination and reduced food longevity and safety. The shift towards reusable, or zero packaging, adds yet another concern over food safety. Bulk refill services in particular raise the potential for contamination, adulteration, and food fraud that will need to be addressed. This presents a conundrum, balancing these immediate safety risks against the long-term consequences of the plastic packaging on human and environmental health and pollution. While these are not new challenges, if introduced at scale across the UK, they require innovative solutions from retailers, and could demand significantly greater monitoring activities.

7.6.5 Regulation

From the perspective of complexity and long-term impact, packaging is a similar domain as the GMO and GE areas. The rapid advances in material science, sensor technologies combined with chemical and biomarkers and IoT applications will lead to sophisticated smart packaging products. Combined with active industry lobbying for rapid commercialisation of these technologies, regulators need to keep abreast of technology in order to be able to understand the potential advantages and risks of the technology. When it comes to regulatory measures for packaging there has to be delineation between different groups of packaging because a sweeping one-size-fits-all regulatory framework or guidelines will not work given the complexity of some of the involved technologies.

UK (and EU) regulatory frameworks for food contact materials, plastic, active and smart packaging are extensive, and the introduction of novel materials follows a strict approvals process (e.g. Tiekstra et al., 2021). However, Tiekstra et al. (2021) suggest that companies are willing to take considered risks by bringing an unapproved product to market to circumvent lengthy approval processes, and in doing so create consumer health and safety risks. Moreover, the effectiveness of these regulations is questionable as there are numerous plastics approved and currently in use for food packaging that are known to contain or potentially contain hazardous chemicals for human or environmental health, e.g. bisphenol A (BPA) in plastics (Muncke, 2021). A particular challenge for regulators approving novel materials is the long-term nature of potential health impacts from bioaccumulates, whereby health effects of novel materials may take many decades to be recognised. Moreover, consumer awareness of these emerging active and smart technologies is low and consumer attitudes are not well understood. Regulators need to ensure physical risks are minimised, along with comprehensive labelling and communication through advertising and media.

In 2019, the UK announced consultations on reducing single-use packaging, including legislation to encourage use of recyclable and reusable/returnable packaging (Growling, 2019). This legislation does not currently prioritise use of biodegradable materials, and existing waste stream processing systems are not set up to handle recycling or composting of such materials. Until these issues are addressed biodegradable packaging is likely to remain niche.

The new legislation is anticipated to play an important role in driving the shift towards reusable/returnable packaging at the retail and manufacturing level, and encouraging consumer adoption (Growling, 2019). Such systems have been in use for decades in the UK so there should not be a requirement for new regulation of these operations; however, as supply and demand for returnable packaging and zero-packaging stores rises there may be a need for greater focus on the systems for dispensing bulk products, cleanliness of consumer provided containers, and greater scrutiny and oversight of the sector to ensure food safety standards are maintained and that contamination and food fraud are adequately contained.

7.6.6 FSA recommendations

- Food adjacent materials used for food packaging play a key role in ensuring food safety for consumers and as such are of critical importance to FSA and therefore FSA must become a development partner in implementing these technologies rather than regulating in responsive mode.

- Emerging evidence on the implications of long-term bioaccumulation of chemicals from plastic packaging, along with a range of emerging nanotechnology packaging materials should be of significant concern to FSA, and therefore expert advice on this topic is recommended.
- A review of regulations for novel packaging may be in order, and FSA should take an active role in promoting (or discouraging) types of packaging through industry engagement and consumer education.
- FSA might consider playing a role in supporting larger-scale market testing of preferred emerging technologies and solutions, and in particular, whether and how to push biodegradable packaging solutions.
- The introduction of edible packaging and the rise in reusable/returnable packaging and zero-packaging solutions requires further investigation to determine the potential safety risks and appropriate policy responses to ensure food safety in this emerging segment.
- Overall, there is great opportunity for regulation to help guide rather than stifle technology towards solutions that provide a systems, rather than a linear approach, to solving problems of food safety.

8 Digital technologies in the food sector

8.1 Digital tools for analysis, decision making and traceability

In this final section we provide a top-level overview of the increasing role of digitization in the food industry and innovations that are likely to impact food safety for consumers.

Automation of traditional manufacturing and industrial practices using smart and connected technology is often referred to as Industry 4.0 (or the fourth industrial revolution). Relative to other sectors, the food industry has been relatively slow to adopt digital technologies, but this is now changing, with innovation occurring rapidly at every stage of the value chain. This includes discrete applications at the field, farm and factory-level, such as automation, robotics, and performance monitoring – mostly aiming at process optimisation; at the consumer level with a multitude of innovative new internet-enabled food distribution platforms and services; and, increasingly at an integrated system level, connecting actors at all stages of the value chain, including supply chain management, and secure and gap-less digital traceability of food items from farm to fork (from production to the end consumer).

Digitization is a vast topic, and to cover all the innovations in the agri-food sector is beyond the scope of this report. For example, there is significant activity in the food-tech start-up scene focused on digital innovation in food delivery and provision of consumer apps and services. The new business models enabled by automation and digitization, such as the delivery platforms, autonomous delivery, dark kitchens, peer-to-peer, and so on, may raise food safety issues, but this risk is not directly caused by the underlying technologies. For the purposes of this review, we focus on technologies that are more directly relevant to food safety monitoring and control.

As digital technologies often reach across several parts of the value chain, as well as out from the value chain into different domains, these technologies can be loosely grouped into three main categories with respect to their impact on consumers and food safety.

a) Digital technologies applied directly to food production processes (such as sensor-based agriculture, traceability, scanning technologies for contaminant detection, monitoring of production and delivery, smart packaging, etc.) where the resulting flow of information is based on input data gathered from the actual food item itself.

b) Digital technologies generating information relevant for food from input data not directly gathered from the actual food item itself – mostly used for supporting decision making and influencing consumer choices (such as genomics data, etc.).

c) The platforms used for aggregating data, transmitting data securely, record keeping, and decision making either autonomously or with human input.

With respect to consumer facing risk, applications in a) and c) can cause considerable food safety risks when misused, or unintentionally failing. Applications in b) are less likely to pose larger-scale risks for consumers.

Over-arching digital innovation areas relevant for food safety include:

- Internet-of-things (IoT), cloud computing, big data, machine-to-machine communication, and remote sensing – enabling rapid communication and structured and unstructured data collection from diverse sources across the global value chain (Marvin et al., 2017; Misra et al., 2020).
- Artificial intelligence, machine learning, digital twins (where a digital simulation is used to monitor real-world performance for unexpected behaviours), etc – offer sophisticated analytics and diagnostic and predictive capabilities, self-monitoring capabilities, and smart machines that can analyse and diagnose issues without the need for human intervention (Defraeye et al., 2021; Koulouris et al., 2021).
- Distributed ledger technology (DLT), such as blockchain – these are decentralised databases existing across several locations or among several

participants, and provide a secure, verifiable, and auditable history of all information stored in the dataset. Immutability, enhanced visibility, transparency and data integrity of DLT systems when used to track food's journey from farm to fork offer the potential to improve trust and food safety in extended food supply chains (Antonucci et al., 2019; Duan et al., 2020; Rejeb et al., 2020).

These are being combined with:

- Data-assisted whole-genome sequencing (*as discussed in section 6*), offering sophisticated tools for rapid and precise identification of food types, contamination and food fraud.
- A wide array of new electronic detection devices (including smart phones), X-ray inspection, smart indicators, connected sensors and RFID tags, and sensors integrated on food packaging (*discussed in section 7*), offering real-time multivariate sensing in processes throughout the value chain.
- Consumer-facing apps enabling access to food data and information for decision making as well as use of social media as effective education and early warning systems (Marvin et al., 2017).

Together, these technologies are reshaping the way data is collected, stored, and used for decision-making, enabling remote or virtual inspections, increasing the levels of automation and communication, and in so doing reducing susceptibility to contamination, human error or deliberate food fraud. These technologies have the potential to transform consumer trust, food safety, transparency, traceability, and accountability, by providing detailed tamper-proof records of a food products' history. The technology should enable rapid response and containment of contamination and pathogen outbreaks within the global food industry and supply chains, so minimising the potential for large-scale public health issues (e.g. Galanakis et al., 2021; Yu et al., 2020).These systems not only provide details on the food itself, but DLT may also provide verifiable detailed certifications of origin, and for example, enhance the credence of claims such as ethically and sustainably sourced.

8.2 Implications of emerging digital tools

8.2.1 Market

The digital transformation is underway, and digital supply chains, and even distributed ledger blockchain technologies are already emerging in some markets. For example, FSA ran successful pilot schemes for blockchain applications in the meat sector in 2018. While most of these digital technologies cannot be considered truly novel any longer, they are evolving at pace, with continuous expansion of capabilities and performance, and numerous start-ups emerging offering novel combinations and novel applications for the technologies. There are challenges with implementation, validation and regulation of these technologies, and blockchain initiatives are still mostly only at pilot stage, and use of DLT for traceability is still undeveloped (Rejeb et al., 2020).

8.2.2 Industry

Digital technologies are bringing important operational benefits for the global food value chain, improving efficiencies and productivity and reducing waste, contamination and food fraud. This will bring benefits to industrial actors throughout the value chain, improving yields and profitability. The technologies themselves are now reasonably well understood, with integrated solutions available off the shelf, and an army of expertise emerging to aid the sector. Numerous food-tech start-ups are emerging offering innovative digital solutions, although food safety and traceability as a segment is seeing a relatively small share of venture funding at present.

Although these digital technologies bring certain benefits, they introduce new business and financial risks. There are significant challenges in introducing the technology into existing operations and integrating with legacy systems, and a need for new operating practices and policies, skillsets and training. Technical integration and interoperability across global supply-chains is a complex challenge and may be hampered by lack of infrastructure, lack of standardisation, and data integrity and data security risks, etc. (Feng et al., 2020). Considerable efforts will be required to build the needed collaboration and coordination to ensure optimum interoperability and harmonisation.

Access to technical skillsets and financial capital for investment may exclude many segments of the industry, favouring larger actors, and discriminating against smaller actors in the value chain (Tripoli & Schmidhuber, 2018). 90% of the global food industry is small to medium sized enterprises (SMEs), who may not have the resources or the baseline level of digitalisation needed for data sharing across digital platforms between organisations, and this may constrain the transformative potential of industry 4.0 in the agri-food sector (Rachel Ward, 2020). Moreover, there are concerns over farm data ownership and privacy issues, market power of major agriculture technology providers and uneven distribution of benefits accruing from digitization (Kosior, 2018).

8.2.3 Consumers

Digital technologies offer consumers the promise of enhanced food safety and far greater transparency. For example, consumers may soon be able to check the full history of the foods they buy simply by scanning a code with their smart phone. This presents consumers with greater choice and control over the foods they choose and consume – based on food safety, nutrition, traceability, and broader sustainability considerations. However, at present studies suggest consumers value food standards certifications, over technological solutions such as blockchain, and are sceptical of the benefits of technologies. Traceability information on locally produced products is of relatively low importance to consumers, and although is more desired for imported products, at the same time is less trusted (e.g. Shew et al., 2021; Zhang et al., 2020). Whether consumers will accept and engage with these technologies, or pay a premium for greater information, remains to be seen, but a lack of consumer engagement may slow the roll-out of consumer-facing technologies. In the short to medium term, deployment of these technologies seems most likely to be at the business-to-business level (B2B) rather than business-to-consumer (B2C); nonetheless, this should still bring big benefits for food safety for consumers.

8.2.4 Food Safety

Advanced traceability systems combined with sophisticated analytical tools for direct authenticity testing and smart tools (e.g. remote or virtual inspections) bring full farm-to-fork tracking of commodities and foods, greater transparency for consumers and regulators, and the ability to identify and respond rapidly to biosecurity issues such as contamination and outbreaks of foodborne disease (Galanakis et al., 2021).

Many of the emerging agri-food technologies identified in this report, such as 3D food printing, and valorisation of waste bioresources (*see section 3*), alternative sources of protein (*section 4*), synthetic biology including gene editing and lab-grown proteins (*section 5*), while offering many potential benefits, also present considerable food contamination, food fraud and authenticity concerns. Digital technologies, underpinned by robust and secure distributed ledgers, may greatly help to tackle these emerging challenges, cut down on fraud and falsified reports, and reduce the risks associated with these emerging technologies.

On the other hand, these technologies are not infallible, and there will always be parts of the system that cannot be controlled entirely through technology. Foods are commodities, shipped and processed in bulk, and even if a shipment is tracked precisely, it is impossible to track every grain or every piece of fruit within a container. Human errors can be greatly reduced, but not eliminated from the system; problems can be more readily detected, but again not entirely eliminated; and malicious cyber-attacks, or hardware/software failures within such complex automated systems raise the prospect of mislabelling or misinforming on millions of items creating serious public health issues.

Moreover, the reach of these technologies is likely to be limited particularly at the far ends of supply-chains, due to high costs or lack of access to technologies, complexity may introduce mistakes, and even the most sophisticated systems are not immune to deliberate fraudulent abuse (Birkel et al., 2019).

8.2.5 Regulation

Duan et al. (2020) identify five potential challenges to DLT-based traceability systems, including lack of deeper understanding of blockchain, technology difficulties, raw data manipulation, difficulties of getting all stakeholders on board in an often fast paced, profit maximising industry setting, and the deficiency of regulations.

Key to implementing global traceability solutions is the need for unified standards and regulations, and the sharing of data among all actors of the value chain. For example, as discussed in *section 6.1*, using genomics for food safety, will require building, maintaining, and sharing widely of a vast global database of DNA sequencies. To date, regulations on technologies such as blockchain, and obligations on transparency reporting are not consistent across jurisdictions creating challenges for adoption (e.g. Krzyzanowski Guerra & Boys, 2021). There are also legal barriers around confidentiality and intellectual property issues associated with data sharing that further inhibit adoption. The regulatory frameworks for supply-chain transparency, and enabling frameworks and regulatory oversight for these new digital technologies will need to evolve to keep pace with industry change and evolving demands (Feng et al., 2020).

Moreover, regulators need to pay close attention to the ways in which these emerging technologies might be subject to cyber-attacks, deliberate abuse and sophisticated digital fraud. A particular concern arises from the nature of the technology sector, made up of numerous start-ups, often operating in stealth mode to protect IP, globally dispersed, and with rapid development and deployment cycles that generally fall outside the regulatory focus, and quite possibly outside existing regulatory frameworks. The predisposition of this technology sector towards releasing partially proven solutions onto the market, with the aim of developing the technology and resolving software problems while already in use, presents an additional level of risk. While this has become an acceptable approach for software development in many sectors, it should be of great concern for safety-critical applications such as food safety and public health. In parallel with the software, pressure to rush new food-contact sensor technologies to market (such as smart and intelligent packaging solutions as discussed in *section 7*), may introduce risks of sensor failures, and other food safety risks associated with contamination with nanoparticles or other compounds. Regulators will need to monitor emerging solutions in the start-up space and develop a regulatory framework to ensure that food safety is embedded in the software and hardware solutions from the outset.

8.2.6 FSA recommendations

- This is a rapidly evolving area that has the potential to greatly enhance food safety and public health. FSA needs to remain at the forefront of exploring and enabling adoption of innovative solutions, and working with industry to pilot new technologies, and ensure systems are developed, tested and deployed effectively.
- The two technology applications observed – generating information directly related to the food product (often directly in contact with food), and those generating indirect data – present different challenges. More vigilance will be required for the first application, and a correspondingly structured approach to capturing misuse will be required.
- The regulatory environment is complex and needs further investigation to better understand where current regulation may be inhibiting innovation and adoption, and to understand the intervention points and required actions to accelerate uptake, while ensuring system validity and integrity and food safety risks are addressed at source to protect consumers and public health.
- FSA will need to support the development of data standards, and the validation, review and scrutiny of digital technologies. FSA should also consider how independent governance might be established to support transparency and trust in these emerging systems (Rachel Ward, 2020), and reduce information asymmetry in global value chains.
- Specific investment and support are needed for SMEs to enable uptake across the entire value chain. FSA should consider how best to develop tools and training to support accessibility and build the skills and expertise to apply these technologies and encourage broader implementation.
- A key role for FSA will also be to inform consumers on how these new technologies work and build consumer confidence in these emerging systems to support the broader adoption and roll-out through retail to consumers.

9 Conclusions

9.1 Summary of emerging technologies

This evidence assessment review identified a range of technologies, that are emerging, or have emerged but not yet been fully commercialised or adopted in the UK food system. They have the potential to materially impact food safety and public health both positively and negatively. These technologies can be grouped into the following technology fields:

1. **Food production and food processing:** Indoor farming; 3D food printing; Food side/by-products (waste to feed/food); Novel non-thermal processing; Novel pesticides/alternative pest control (*Section 3*)
2. **Novel sources of protein:** Alternative sources of protein such as insects and microalgae for human consumption; and as novel feedstocks for animals (*Section 4*)
3. **Synthetic biology:** Microorganisms for biosynthesis; GM/GE modified plants and functional foods; Gene modified livestock; Gene drives; Lab-based animal meat, fats, eggs, dairy (*Section 5*)
4. **Genomics applications along the value chain:** Genomics information for food traceability; Selective breeding (animals and crops); Use of microbiome information; Personalised nutrition based on microbiome; Nutritional epigenetics tools (*Section 6*)
5. **Novel packaging technologies:** Active packaging; Intelligent and smart packaging; Nanotechnologies; Biodegradable and edible films; Reusable packaging and zero packaging (*Section 7*)
6. **Digital technologies in the food sector:** Digital tools for analysis, decision making and traceability (*Section 8*)

Many of these technologies are currently at the laboratory or pilot stage and seem to be far from market, so it may be tempting to view their regulation as a remote problem that needs attention only after they have gained more traction. However, a real structural problem underlying most of these technologies is that the software development model (unleashing unfinished versions of a product on the market to test its uptake and performance) is increasingly finding its way into the world of hardware and material product development. This is already observed in food packaging where companies may release uncertified products to avoid the lengthy regulatory approvals processes. This means that the regulators need to engage with sophisticated technologies, such as GMO, GE, synthetic biology, and food packaging, from the very early stage in order to be able to exert influence early on and help these industries build safety into their products from the start – in the same way as software development now aims to build security into the product from the start.

9.2 The direction of travel of emerging technologies

The agri-food technology sector has seen rapid development over the past decade, driven by significant venture capital inflows ramping up investment in speculative technologies, and a search from the major multinationals for new sources of income and growth (by often acquiring new technology start-ups that have developed and tested minimally viable prototypes). Increasingly the industry is experiencing a strong technology push, potentially bringing products and services to market for the sake of the technology rather, than satisfying a real consumer need. These technologies may not necessarily be in the best interests of society and the environment in the short or longer-term.

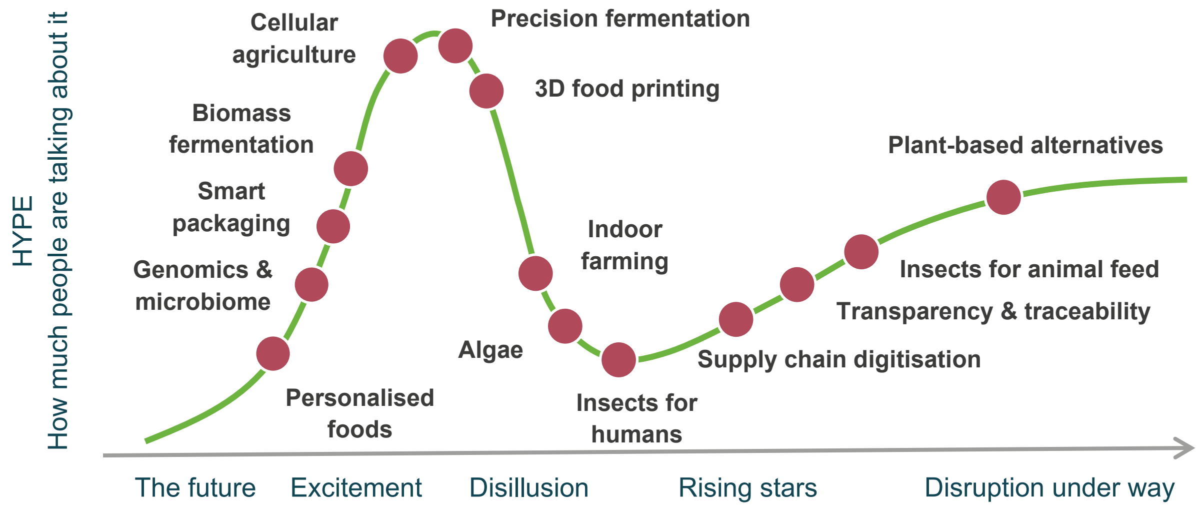
Many of the novel foods and food processing technologies presented in this report represent the cultivation and processing of foods in very artificial manmade environments and processes. For example, indoor farming, 3D printing, synthetic biology, novel non-thermal treatments, and sophisticated packaging solutions. Food products are increasingly created in highly sterile environments largely free of the everyday contaminants that humans have evolved to deal with. Human immune systems are strongly shaped by exposure to food that is not sterile, and as part of human evolution we have become able to survive in non-sterile environments. Modern heavily processed foods and processes remove this opportunity by making everything unnaturally clean, and this presents a real and serious issue for human health and healthcare systems in the longer-term. FSA needs to consider whether food safety regulations should address this issue.

Moreover, the innovations such as 3D foods, and the ability to create “fresh-like” products through sophisticated processing and packaging, are likely to diminish the nutritional value of the foods we consume. Over time, the cumulative effects may be significant for human health, in the same way that previous innovations around sugars, fats, and existing ultra-processed foods have proven over time to be damaging to human health. Again, what role should FSA play in shaping future nutrition.

These emerging technologies should be monitored and promoted by FSA where they contribute in some way to a healthier and more secure food system, while at the same time staying vigilant on long term health issues for humans, and possibly their environmental impact and sustainability, drafting regulation accordingly. The issues raised through this report consistently point to the need for a novel systems-oriented regulatory framework for the food sector.

9.3 Maturity of the emerging technologies

The emerging technologies identified are at differing levels of development and maturity and have varying potential for adoption and impact on the food system. Figure 5 presents a Gartner curve of the agri-food technology sector, illustrating a qualitative assessment of the level of hype, versus the maturity of the technologies.



(Adapted from DigitalFoodLab, 2021)

Figure 5 Gartner hype curve

Understanding the position on the curve helps to distinguish between the hype and the reality. Many of the technologies reviewed are still at a very early stage in their maturity, still in lab or pilot scale projects, and even where commercialised may still be artisanal curiosities, rather than of mainstream interest.

9.4 Summary of implications of the emerging technologies

This rapid evidence assessment explored five research questions that have been discussed in depth in this report. The following five tables present a qualitative assessment and summary of the key findings for each question.

Table 1: What are the emerging technologies likely to impact on the UK food system within the next 15 years?

The table provides a qualitative assessment of the likely timeframes to reach a scale at which the technology might have material impact and disrupt the existing food system. The current level of maturity of the technology is highlighted, along with the primary actors driving the innovation at present (academia/national research centres, start-ups, or existing industry incumbents), and an assessment of where impacts will occur in the value chain. In **Table 2** we provide an overview of the potential contribution, positive and negative, towards environmental sustainability, by considering the use of land, water, energy and non-renewable resources, potential impact on pollution and waste, environmental degradation, and long-term contribution to societal sustainability through health and wellbeing.

Table 3: What is the likely impact of the technologies on how food businesses operate?

Here we summarise the requirements for new/alternative inputs (e.g., feed, waste streams, etc.), equipment and process changes, monitoring and control systems, new business models, and new business eco-systems. Business model and business eco-system changes include emergence of new industry segments, new suppliers/partner relationships, shift towards localised production, direct producer/processer-to-consumer sales, circular business models, etc). Understanding where business operations may change provides an indication of where food safety might be compromised through the introduction of pathogens, toxins, quality variability, and so on.

Table 4: What is the likely impact of the technologies on how consumers make choices about what they consume?

This table summarises where a technology enables greater transparency (visibility of the supply chain, food origin, environmental impact, etc); enhanced consumer trust in the perceived/actual food quality and authenticity; consumer convenience and choice; and potential for enhanced nutrition. The table also indicates where consumers lack understanding of the technology because it is, from current reporting, perceived as too complicated or opaque, and the related issue of consumer resistance to the technology (food/technology neophobia). Finally, we indicate where there is likely to be a cost impact for the consumer of the emerging technology that may act as a barrier to adoption.

Table 5: What are the major risks and opportunities that these technologies might afford for improving food safety for consumers?

This table presents a qualitative assessment of the risks and benefits for food safety presented by each of the emerging technologies, in terms of allergens, contamination and toxicity, and food fraud (traceability, authenticity, etc). We highlight where innovations, due to their nature, may create regulatory and oversight challenges for FSA. We also highlight where technologies may present malnutrition and long-term human health concerns, and finally, identify where technologies may be particularly susceptible to accidental misuse, system failure, or deliberate malicious attack.

Table 6 addresses the question: What are the risks and opportunities that the emerging technologies present for the regulatory framework?

This table, identifies where an emerging technology may present a potential impact from outside of the UK regulatory framework (e.g. GE crops and animals raised overseas entering the UK food system); highlights where further in-depth research on long-term human health implications is required; where there will be requirements for new certification and approvals (e.g. new regulations around use of waste by-products); where new oversight, monitoring and compliance issues will arise; and where there will be a need to educate consumers and raise awareness of the beneficial impacts of new technologies to support widespread uptake. We highlight were current regulations present a barrier to broader uptake – these include organic labelling restrictions on indoor farming; restrictions on using food by-product streams; novel foods restrictions; and restrictions on use of GE technologies for synthetic biology. Finally, we prioritise on a scale of 1-5 (low – high) the need for regulatory intervention.

Table 1 Timeframes and potential impact on UK food system

Food production and processing technologies

Emerging Technology	Time frame (S,M,L)	Maturity (1-5)	Primary actors	Value chain impact points
Indoor farming	M	2/3	NE	2,5
3D food printing	M	2/3	NE	3,4,5,6
Food side and by-products	M	2	IN	2,3,7
Novel non-thermal processing	S-M	1	IN	3,4
Novel pesticides/pest control	S-M	1/2	NE/IN	1,2

Novel sources of protein

Emerging Technology	Time frame (S,M,L)	Maturity (1-5)	Primary actors	Value chain impact points
Alternative proteins (insects, etc.) as food	M	2	NE	2,3
Novel feedstocks for livestock/aquaculture	S	3	NE/IN	1,2

Synthetic biology/genome editing

Emerging Technology	Time frame (S,M,L)	Maturity (1-5)	Primary actors	Value chain impact points
GM/GE plants / livestock / micro-organisms	S, M-L	3	NE/IN	1,2,3
Lab-based animal meat, fats, eggs, dairy	M-L	1	NE	2,3

Genomics applications along the food value chain

Emerging Technology	Time frame (S,M,L)	Maturity (1-5)	Primary actors	Value chain impact points
Genomics for decision-making/agriculture	M-L	2	ACRD/NE/IN	1,2,3,4,5,6,7
Genomics for personalised nutrition	L	1	AC	6

Novel food packaging technologies

Emerging Technology	Time frame (S,M,L)	Maturity (1-5)	Primary actors	Value chain impact points
Active / intelligent / smart packaging	S-M	3	IN	3,4,5,6
Nanotech / biodegradable / edible films	M-L	1	ACRD/IN	3,4,5,6,7
Reusable / zero packaging	S-M	2	NE/IN	3,4,5,6,7

Digital technologies in the food sector

Emerging Technology	Time frame (S,M,L)	Maturity (1-5)	Primary actors	Value chain impact points
Digital tools for decisions/traceability	S-M	3	IN	1,2,3,4,5,6,7

Anticipated timeframe for impact on existing value chain: (S) Short-term - within 3 years; (M) Medium-term - 3-5yrs; (L) Long-term - 5-10 years.

Maturity: (1) Lab/pilot; (2) Curiosity/niche; (3) Taking-off; (4) Mass market; (5) Global mass-market

Primary actors driving innovation: (ACRD) Academia/R&D; (NE) new entrants/start-ups; (IN) Incumbents (for example, large multinationals)

Point of impact on food value chain: (1) Inputs; (2) Farm; (3) Processing; (4) Packaging and distribution; (5) Retail/food services; (6) Consumer/food preparation; (7) Waste/recycling

Table 2 Sustainability implications of emerging technologies

Food production and processing technologies

Emerging Technology	Potential positive contributions to sustainability (environmental and societal)	Potential negative impacts on sustainability (environmental and societal)
Indoor farming	Free of pathogens (maybe)	Artificial growing environment, too sterile, energy and equipment
3D food printing	Use of by-products and waste food	Energy and equipment for ingredients & printing, nutrition
Food side and by-products	Use of waste stream and by-products	Processed foods, nutritional risk
Novel non-thermal processing	Reduced food waste, energy saving	Nutritional value, food risk
Novel pesticides/pest control	Potential to shift to more natural solutions	Many unknowns regarding long term environmental impact

Novel sources of protein

Emerging Technology	Potential positive contributions to sustainability (environmental and societal)	Potential negative impacts on sustainability (environmental and societal)
Alternative proteins (insects, etc.) as food	Reduced animal farming, water, land use, GHG	Artificial environment, unknown implications for health
Novel feedstocks for livestock/aquaculture	Reduced fish catch, water, land use, GHG	Unknown implications for animal health

Synthetic biology/genome editing

Emerging Technology	Potential positive contributions to sustainability (environmental and societal)	Potential negative impacts on sustainability (environmental and societal)
GM/GE plants / livestock / micro-organisms	Increase diversity, reduce need for antibiotics, pesticides, ability to use/ restore degraded land, reduced water use	Potential for off-target impacts on nature/indigenous crops/animals, and human health
Lab-based animal meat, fats, eggs, dairy	Reduce dependence on animal farming, water, land use, GHGs	High energy use, disposable plastic, lack of nutritional value

Genomics applications along the food value chain

Emerging Technology	Potential positive contributions to sustainability (environmental and societal)	Potential negative impacts on sustainability (environmental and societal)
Genomics for decision making/agriculture	Improved efficiency, productivity, reduced waste, transparency	Potential for misuse, off-target, energy use, equipment
Genomics for personalised nutrition	Optimised use of food resources	Potential for misuse, off-target nutrition

Novel food packaging technologies

Emerging Technology	Potential positive contributions to sustainability (environmental and societal)	Potential negative impacts on sustainability (environmental and societal)
Active / intelligent / smart packaging	Reduced food waste	Plastic waste, risk of food contamination
Nanotech / biodegradable / edible films	Biodegradable materials	Plastic waste, risk of food contamination, unknown impact of nanoparticles
Reusable / zero packaging	Reduced plastic waste	Risk of food contamination, reverse logistics requirements

Digital technologies in the food sector

Emerging Technology	Potential positive contributions to sustainability (environmental and societal)	Potential negative impacts on sustainability (environmental and societal)
Digital tools for decisions/traceability	Resource efficiency, productivity, reduced waste, improved transparency	Energy and hardware demands, susceptibility to outage, cyber attack

Table 3 Emerging technologies – Impact on business operations

The dash in the tables indicates the qualitative assessment indicating where the emerging technology is anticipated to impact or have significant influence on business operations.

Food production and processing technologies

Emerging Technology	New material inputs	New equipment/ processes	New quality control & monitoring systems	New business models	New industry eco-system/ supply-chains
Indoor farming	-	-	-	-	-
3D food printing	-	-		-	-
Food side and by-products	-	-		-	-
Novel non-thermal processing		-	-		
Novel pesticides/pest control	-		-		

Novel sources of protein

Emerging Technology	New material inputs	New equipment/ processes	New quality control & monitoring systems	New business models	New industry eco-system/ supply-chains
Alternative proteins (insects, etc.) as food	-	-	-		-
Novel feedstocks for livestock/aquaculture	-	-	-		-

Synthetic biology/genome editing

Emerging Technology	New material inputs	New equipment/ processes	New quality control & monitoring systems	New business models	New industry eco-system/ supply-chains
GM/GE plants / livestock / micro-organisms	-		-		
Lab-based animal meat, fats, eggs, dairy	-	-	-		-

Genomics applications along the food value chain

Emerging Technology	New material inputs	New equipment/ processes	New quality control & monitoring systems	New business models	New industry eco-system/ supply-chains
Genomics for decision-making/agriculture		-	-		
Genomics for personalised nutrition				-	-

Novel food packaging technologies

Emerging Technology	New material inputs	New equipment/ processes	New quality control & monitoring systems	New business models	New industry eco-system/ supply-chains
Active / intelligent / smart packaging		-	-		
Nanotech / biodegradable / edible films		-	-		
Reusable / zero packaging		-		-	-

Digital technologies in the food sector

Emerging Technology	New material inputs	New equipment/ processes	New quality control & monitoring systems	New business models	New industry eco-system/ supply-chains
Digital tools for decisions/traceability		-	-	-	

Table 4 Emerging technologies – Impact on consumers

The dash in the tables indicates the qualitative assessment indicating where the emerging technology is anticipated to impact or have significant influence on business operations.

Food production and processing technologies

Emerging Technology	Enhanced transparency	Enhanced food safety /trust	Increased consumer convenience	Potential to enhance nutrition	Complicated/ confusing technology	Consumer resistance	Potential cost impact
Indoor farming		-	-	-		-	-
3D food printing			-		-	-	-
Food side and by-products				-	-	-	
Novel non-thermal processing		-	-	-	-	-	-
Novel pesticides/pest control		-		-	-	-	-

Novel sources of protein

Emerging Technology	Enhanced transparency	Enhanced food safety /trust	Increased consumer convenience	Potential to enhance nutrition	Complicated/ confusing technology	Consumer resistance	Potential cost impact
Alternative proteins (insects, etc.) as food				-		-	
Novel feedstocks for livestock/aquaculture				-		-	

Synthetic biology/genome editing

Emerging Technology	Enhanced transparency	Enhanced food safety/trust	Increased consumer convenience	Potential to enhance nutrition	Complicated/ confusing technology	Consumer resistance	Potential cost impact
GM/GE plants / livestock / micro-organisms				-	-	-	
Lab-based animal meat, fats, eggs, dairy					-	-	-

Genomics applications along the food value chain

Emerging Technology	Enhanced transparency	Enhanced food safety/trust	Increased consumer convenience	Potential to enhance nutrition	Complicated/ confusing technology	Consumer resistance	Potential cost impact
Genomics for decision-making/agriculture	-	-			-	-	-
Genomics for personalised nutrition				-	-		-

Novel food packaging technologies

Emerging Technology	Enhanced transparency	Enhanced food safety/trust	Increased consumer convenience	Potential to enhance nutrition	Complicated/ confusing technology	Consumer resistance	Potential cost impact
Active / intelligent / smart packaging	-	-	-		-	-	-
Nanotech / biodegradable / edible films			-		-	-	-
Reusable / zero packaging			-			-	-

Digital technologies in the food sector

Emerging Technology	Enhanced transparency	Enhanced food safety/trust	Increased consumer convenience	Potential to enhance nutrition	Complicated/confusing technology	Consumer resistance	Potential cost impact
Digital tools for decisions/traceability	-	-			-		

Table 5 Emerging technologies – Impact on food safety

Food production and processing technologies

Emerging Technology	Food safety risk			Enhanced food safety			Other factors		
	Allergens	**Contaminants and toxicity**	**Food fraud**	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**FSA oversight**	**Nutritional concerns**	**Failure/ misuse risk**
Indoor farming	No	Med	No	Med	Med	Low		-	
3D food printing	Med	Med	High	No	No	No	-	-	-
Food side and by-products	Med	High	High	No	No	No	-		
Novel non-thermal processing	Low	Med	No	No	Med	No			
Novel pesticides/pest control	Low	Low	No	No	Med	No	-		-

Novel sources of protein

Emerging Technology	Food safety risk			Enhanced food safety			Other factors		
	Allergens	**Contaminants and toxicity**	**Food fraud**	**Allergens**	**Contaminants and toxicity**	**Food fraud**	**FSA oversight**	**Nutritional concerns**	**Failure/ misuse risk**
Alternative proteins (insects, etc.) as food	Low	High	High	No	No	No		-	
Novel feedstocks for livestock/aquaculture	Low	Med	Med	No	No	No	-	-	

Synthetic biology/genome editing

Emerging Technology	Food safety risk			Enhanced food safety			Other factors		
	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	FSA oversight	Nutritional concerns	Failure/ misuse risk
Alternative proteins (insects, etc.) as food	Med	Med	No	High	High	No		-	
Novel feedstocks for livestock/aquaculture	Med	High	High	No	High	High	-	-	

Genomics applications along the food value chain

Emerging Technology	Food safety risk			Enhanced food safety			Other factors		
	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	FSA oversight	Nutritional concerns	Failure/ misuse risk
Genomics for food safety/agriculture	No	No	No	Low	High	High			-
Genomics for personalised nutrition	No	No	No	High	High	No	-		-

Novel food packaging technologies

Emerging Technology	Food safety risk			Enhanced food safety			Other factors		
	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	FSA oversight	Nutritional concerns	Failure/ misuse risk
Active / intelligent / smart packaging	Low	Low	No	Low	Med	Med	-		-
Nanotech / biodegradable / edible films	Med	Med	No	Low	Med	No	-		-
Reusable / zero packaging	High	High	High	No	No	No	-		-

Digital technologies in the food sector

Emerging Technology	Food safety risk			Enhanced food safety			Other factors		
	Allergens	Contaminants and toxicity	Food fraud	Allergens	Contaminants and toxicity	Food fraud	FSA oversight	Nutritional concerns	Failure/ misuse risk
Digital tools for decisions/traceability	No	No	No	High	High	High			-

High food safety risk
Medium food safety risk
Low food safety risk
No anticipated impact

High improvement in food safety
Medium improvement in safety
Low improvement in food safety
No anticipated impact

Food safety risks: Allergens (milk, wheat, peanuts, tree nuts, fish, shellfish, soy, eggs, etc). **Contamination and toxicity** (Biological: pathogens, bacteria, viruses, etc., and unintentional or not well understood molecular changes of food product due to complexity of processing; Chemical: pesticides, antibiotics, hormone disruptors, machine oils, etc.; Physical hazards: glass, hair, etc.). **Food fraud** (Adulteration, misuse of additives, mislabelling, unauthorised GM, past use-by-date, origin and authenticity and intellectual property fraud).

Dashes indicate that a qualitative assessments a indicating where the emerging technology is anticipated to present regulatory and enforcement challenges, nutritional concerns, and risk of failure or accidental misuse.

Table 6 Emerging technologies – Implications for UK regulatory framework

The dashes indicate where the emerging technologies raise issues for the UK regulatory framework and regulatory bodies.

Food production and processing technologies

Emerging Technology	Potential impact from outside UK	Uncertain health outcomes	New certification / regulation required	New monitoring & compliance requirements	Consumer education and choice signalling	Inhibitive regulation in place	Regulatory action required (1-5, low-high priority)
Indoor farming		-	-	-	-	-	2
3D food printing		-		-	-		2
Food side and by-products	-	-	-	-		-	4
Novel non-thermal processing	-	-	-		-		4
Novel pesticides/pest control	-	-	-	-	-		4

Novel sources of protein

Emerging Technology	Potential impact from outside UK	Uncertain health outcomes	New certification / regulation required	New monitoring & compliance requirements	Consumer education and choice signalling	Inhibitive regulation in place	Regulatory action required (1-5, low-high priority)
Alternative proteins (insects, etc.) as food	-	-	-	-	-	-	4
Novel feedstocks for livestock/aquaculture	-	-	-	-		-	3

Synthetic biology/genome editing

Emerging Technology	Potential impact from outside UK	Uncertain health outcomes	New certification / regulation required	New monitoring & compliance requirements	Consumer education and choice signalling	Inhibitive regulation in place	Regulatory action required (1-5, low-high priority)
GM/GE plants / livestock / micro-organisms	-	-	-	-	-	-	4
Lab-based animal meat, fats, eggs, dairy	-	-	-	-	-	-	3

Genomics applications along the food value chain

Emerging Technology	Potential impact from outside UK	Uncertain health outcomes	New certification / regulation required	New monitoring & compliance requirements	Consumer education and choice signalling	Inhibitive regulation in place	Regulatory action required (1-5, low-high priority)
Genomics for decision-making/agriculture	-		-	-			4
Genomics for personalised nutrition		-	-		-		2

Novel food packaging technologies

Emerging Technology	Potential impact from outside UK	Uncertain health outcomes	New certification / regulation required	New monitoring & compliance requirements	Consumer education and choice signalling	Inhibitive regulation in place	Regulatory action required (1-5, low-high priority)
Active / intelligent / smart packaging	-	-	-	-	-		4
Nanotech / biodegradable / edible films	-	-	-	-	-		3
Reusable / zero packaging	-	-	-	-	-		4

Digital technologies in the food sector

Emerging Technology	Potential impact from outside UK	Uncertain health outcomes	New certification / regulation required	New monitoring & compliance requirements	Consumer education and choice signalling	Inhibitive regulation in place	Regulatory action required (1-5, low-high priority)
Digital tools for decisions/traceability	-		-	-	-		5

9.5 FSA priorities and strategic response

New regulation will be required to facilitate safe uptake of some of these emerging technologies, to encourage investment, and provide consumer confidence for widespread acceptance and adoption.

At the same time, some of the technologies present a high potential risk to food safety, yet they are currently niche, and widespread adoption within the next 5-10 years is considered unlikely; whereas, other technologies may represent less risk individually, but their broad application to traditional industry presents a higher likelihood of significant influence on overall UK and global food safety. Figure 7 presents a qualitative risk-proximity assessment of the food safety risks versus likelihood of widespread adoption within the next decade. The figure illustrates two primary strategic focus areas for FSA.

Regulation focus: The first grouping, in the top right quadrant of Figure 7, are technologies with the greatest potential to introduce food safety risk. These technologies may offer benefits for the food system and consumers so they should not be discouraged; however, regulatory oversight is essential to avoid negative side effects. These technologies should be the primary focus for FSA in terms of on-going monitoring and evaluation and regulatory development to ensure that the risks are adequately managed. In this report **two major areas of emerging technology** are identified that are of high complexity utilising a number of science and technology fields to deliver solutions and products to industry and consumers, hence impacting the food system in a highly dynamic and networked fashion. These are **Synthetic Biology** and **Novel Food Packaging Technologies**. These will require sophisticated policy responses to ensure the benefits of these technologies and commercial pressures are adequately balanced with the need for food safety, human and environmental health.

Supporting adoption: The second grouping, in the bottom right quadrant, are technologies with the greatest potential to enhance food safety. These technologies should be encouraged by FSA through appropriate regulatory changes and support to encourage research and development, investment and entrepreneurship. Public education will be necessary for consumer-facing technologies to raise awareness and encourage widespread acceptance and adoption. Of these, **a third major group** of technologies, the **Digital Technologies**, have considerable potential to increase traceability and therefore safety of food production processes and supply chains. There are considerable implementation challenges, but the main challenge with the fast growth and adoption of these technologies lies in their systemic effects which in turn translates into systemic risks that regulators will need to manage.

The remaining technologies, in the left-hand quadrants should not be ignored, but their impact on the food system will be slower to materialise, so FSA's primary strategic response should be on-going monitoring of developments at this stage. However, as discussed previously, the dynamic nature of the technology sector means that FSA may have to engage much sooner in the technology life cycle than might have been the case in the past.

Anticipated impact on food safety		Likelihood of large-scale implementation within next decade: Low	Likelihood of large-scale implementation within next decade: High
	Creates food safety risk	**Monitor development** - Indoor farming - 3D food printing - Lab-based animal meat, fats, eggs, dairy	**Regulation focus areas** - Food side and by-products - Novel non-thermal processing - Novel pesticides/pest control - Novel feedstocks for animals - Alternative proteins (insects, etc.) - Microorganisms for biosynthesis - GM/GE modified plants & livestock - Active/intelligent/smart packaging - Nanotech/biodegradable/edible films - Reusable/zero packaging
	Enhances food safety	**Monitor development** - Genomics for personalised nutrition	**Supporting adoption** - Genomics for food safety/agriculture - Digital tools for analysis, decision making and traceability

Figure 5 Emerging technologies – Risk vs. proximity, and strategic response

9.5.1 Short-term FSA priorities (within 3 years)

In the immediate future **digital technologies** seem likely to have the most notable impact on improving food safety via improved electronic traceability/authenticity testing technologies, and this is already underway. Digital innovation is occurring at every stage of the value chain, and increasingly at an integrated system level. **Distributed ledger technologies, Internet of Things, digital twins, artificial intelligence, consumer-facing apps**, combined with a wide array of **new detection**

devices, smart indicators, and sensors integrated on food packaging are already being successfully implemented in the food industry.

9.5.2 Medium-term FSA priorities (3 to 5 years)

In the medium term, the impact of **innovations in pesticides, non-thermal food processing, and food packaging** are likely to be significant given their broad application across traditional industry. **Alternative proteins**, such as insects, are gaining traction, but their impact in the UK is likely to be greatest in **animal and fish feedstock** rather than direct human consumption.

Novel technologies such as **indoor farming, lab-grown meats, and food printing** may have impact on the food system in the medium to long-term, but their uptake is far from certain, and they well may remain niche sectors. While regulation will certainly be required, these will probably be a secondary priority for FSA in the medium-term.

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

In the longer-term the role of **genomics in informing the food system** and offering **personalised nutrition** present perhaps the most significant opportunities for change and enhancing food safety and food quality.

9.6 Limitations of study

The agri-food technology sector has been evolving rapidly over the past three decades, with significant investment and innovation across the world. This has led to an increasingly dynamic and efficient innovation ecosystem of food relevant technologies. Although globally many novel technologies are currently tested locally under considerably different regulatory frameworks, this report is believed to have captured the most salient technologies immediately relevant to the UK food system and to FSA.

The findings reflect expert opinions on the risks and opportunities of these technologies, but there may be other risks, as of yet, unrecognised. Quantitative and qualitative assessment of the relative significance and risks of each technology is poorly addressed in the literature. This report has attempted to prioritise the emerging technologies based on the available information, but this should be viewed as guidance only. More in-depth study is needed to more precisely determine the risk profiles these technologies represent, and to develop detailed regulatory responses to ensure safe deployment across industry.

9.7 Recommendations for future research and analysis

Further in-depth research is required to better understand the food safety and health implications for most of these emerging technologies and to develop appropriate policy responses. Further research falls into two types – detailed review of the relevant literature and practice; and further commissioned scientific research to explore the identified gaps in knowledge. Table 7 summarises the areas of further research required.

Table 7 Recommendations for future research and analysis

Food production and processing technologies

Emerging Technology	Further study recommended	Research and development required
Indoor farming	Management of risk of contamination and disease.	Impact of use of plastics in production systems, and artificial environment.
3D food printing	Not applicable	Nutritional impact of 3D printed food – e.g., lack of fibre
Food side and by-products	Review of emerging field in more depth to identify potential risk areas	Development of extraction/ purification technologies
Novel non-thermal processing	Review of emerging field in more depth to identify potential risk areas	Ongoing development of new technologies/upscaling of existing technologies
Novel pesticides/pest control	Review of emerging field in more depth to identify potential risk areas	Ongoing development of new technologies

Novel sources of protein

Emerging Technology	Further study recommended	Research and development required
Alternative proteins (insects, etc.) as food	Further review of risks of allergens, feedstuffs	Nutritional impact on long-term health of consumption
Novel feedstocks for livestock/aquaculture	Further review of risks of allergens, feedstuffs	Nutritional impact on long-term health of consumption

Synthetic biology/genome editing

Emerging Technology	Further study recommended	Research and development required
GM/GE plants / livestock / micro-organisms	Expert review of the potential risks, and how to regulate	Further research into long-term health implications
Lab-based animal meat, fats, eggs, dairy	Expert review of the potential risks, and how to regulate	Further research into long-term health implications

Genomics applications along the food value chain

Emerging Technology	Further study recommended	Research and development required
Genomics for decision making/agriculture	Expert review of the potential uses in food safety	Ongoing development of the technologies
Genomics for personalised nutrition	Not applicable	Ongoing development of the technologies

Novel food packaging technologies

Emerging Technology	Further study recommended	Research and development required
Active / intelligent / smart packaging	Expert review of use of novel materials and plastics in packaging	Ongoing development of the technologies
Nanotech / biodegradable / edible films	Expert review of use of novel materials and plastics in packaging	Ongoing development of the technologies
Reusable / zero packaging	In-depth review of potential impacts of reusable/no packaging solutions	Ongoing development of the technologies/upscaling of existing technology

Digital technologies in the food sector

Emerging Technology	Further study recommended	Research and development required
Digital tools for decisions/traceability	Detailed review of the potential risks and mitigation strategies with emerging systems	Ongoing development of the technologies

Of the above, three specific topics are recommended for deeper investigation due to their potential for affecting a large consumer segment in the short to medium term:

- **Novel animal and fish feedstocks:** Insect proteins are already established for aquaculture and anticipated to grow substantially over the coming decade. However, the long-term implications on animal health and subsequent human health associated with use of these feedstocks is poorly understood to date. Further research is urgently needed in this area.

- **Food additives:** A wide range of natural additives are being utilised to enhance food nutritional value and other factors, such as food colour and texture. Investigation of all these additives individually was beyond the scope of this report. **Of note**, in the discourse on food risks, numerous reports flagged up cannabinoids including cannabidiol (CBD) and cannabidiolcontaining products as being of particular concern over allergenic and toxicity risks. The market for CBD-infused products is expanding rapidly in the US and could become an important sector in the UK in time. FSA will need to ensure applications of these additives are carefully evaluated and understood and regulate appropriately.

- **Health impact of Hormone Disrupting Chemicals in plastics:** Recent scientific evidence points towards the longer-term impact on animal and human health of hormone disrupting chemicals that can be released from plastic materials when in direct contact with food items (packaging) or through plastic exposure of food inputs along the value chain. As these chemicals can affect physiology at very low concentrations causing longer term health effects, more research needs to establish how to assess and test for that risk.

9.8 Related emerging risks for further consideration

This rapid evidence assessment focused on emerging agri-food technologies, but in the course of the research several related and over-arching emerging trends were identified that FSA should consider in the context of future public health. These include:

- **Changing consumer preferences:** Consumers are increasingly demanding raw and minimally-processed foods, with reduced, or no additives and preservatives, and a shift towards less or zero packaging. These trends are creating a greater risk of exposure to foodborne illnesses and contaminants that will need to be addressed.

- **Microbial resistance to antibiotics and pesticides:** Widespread use of antibiotics and chemical pesticides over the past decades has led to the emergence of new pathogens with resistance to current treatments, threatening food production and delivery systems. Novel solutions will become an increasing priority.

- **Plastic contamination and micro-plastics:** Researchers are highlighting the effects of long-term exposure to the chemicals in food-contact plastics (see above). Concerns are also mounting over micro-plastics within the food system (particularly in fish and seafood) and the impact on long-term human health. The implications of this ongoing research may impose major changes in the way food is grown, prepared, and packaged in the future.

- **Public health and nutrition:** Non-communicable diet-related diseases such as obesity, heart disease and diabetes are a major public health issue. There is increasing awareness of the influence of poor nutrition and poor food choices on public health and the urgent need, not just to address food safety, but also food quality and consumer education across the food industry.

10 Recommendations for Policy and Regulation Strategy

Taking the totality of this research into consideration there emerges a strong requirement for FSA to develop a strategic systems approach towards policy and regulation design.

Given the rapid advances in technology and increasing zeal in commercialising technology there is an expectation that regulators take on a role of promoters of innovation and technology solutions. This approach may have its merits to a large extent; however, good regulation needs to strike a balance between enabling economic and commercial activity while fulfilling the commitment to safeguarding the society and consumers against risks and potential harm.

To that effect regulators are increasingly required to engage with state-of-the-art technology in order to be able to support the emergence and growth of new products and services and even new industries while fulfilling their safeguarding role.

In this report two major areas of emerging technology are identified that are of high complexity utilising a number of science and technology fields to deliver solutions and products to industry and consumers, hence impacting the food system in a highly dynamic and networked fashion, and with significant potential implications for the environment and society. These are:

- Synthetic biology (GM/GE plants/livestock, and lab-based animal meat, egg protein and dairy).
- Novel food packaging technologies (active, smart, intelligent packaging; nanotechnology, biodegradable, and edible films).

The nature of these technologies means FSA is required to move from a reactive approach to regulation and policy formation, to an anticipatory dynamic systems approach, which will require several major strategic considerations to be implemented: Develop new expertise in the emerging technologies; adopt a systems approach to regulation design; accelerate regulatory response time; and manage the digital transition.

10.1 Develop further technical expertise

Firstly, it is advisable that FSA considers building deeper long-term ties with experts in various fields of science and technology related to above areas as well as expanding inhouse expertise in assessment and evaluation of such technologies in relation to food. This will enable FSA to engage with industry at different stages of science, technology and product development and act as an informed and competent partner influencing the formation of these technologies with consumer interest and food safety built in from the start.

There are a number of reasons for suggesting a sophisticated and possibly resource intensive approach:

i. Although the above-mentioned technologies may be considered far from market, some with a lead time of a decade or more, the innovation process of product development for hardware/material products is increasingly adopting the software development model. This means releasing incomplete or unfinished versions of a product on the market in small quantities to test its uptake and performance, whereby these test markets consist of many thousands of customers. This means regulators need to engage with such sophisticated technologies from the very early stage in order to be able to exert influence early on and help these industries build safety into their products from the start – in the same way as now the software industry has come to learn that security must be a built-in feature of the software product from the start.

ii. There will be increasing pressure on the regulator to define boundaries of food safety anew. These sophisticated technologies are changing the traditional view of food safety from presence of pathogens/microorganisms or toxic substances to a much wider and complex picture. For example:

    - Apart from lack of major nutrients and vitamins, lab grown meat/protein will lack natural microorganism flora of meat that humans have been consuming through millennia. What is the implication of eating sterile food for our immune system, particularly on its development in children?

- How to balance the unknown risks of nanomaterials on human health against the short to mid-term benefits of smart packaging?
    - How to argue for and promote simple non-technical solutions, such as safe refill packaging despite the pressure of industry for promoting sophisticated smart packaging
- How to define a mutation resulting from Gene Editing as “equivalent to a mutation that could have occurred naturally” and therefore deemed permissible, as is stated by US regulators?
    - What are the scientific boundaries of the risk profile?
    - What is the safe permissible mutation load generated through Gene Editing in a species used as food or feed?

iii. Given the nature of international trade and expected impact of climate change there will be an increasing need for importing food or opportunities to export. This will require the FSA to be able to rapidly assess the permissibility of technologies used in production, processing and packaging of imported food from the UK regulatory perspective. In the same vein FSA can support the UK food industry by providing evidence-based safety certification of UK food products safety.

- It may be relevant to set standards for the end product that can be tested and controlled in the UK but will enforce regulatory measures down the line indirectly in relation with the raw materials. Examples are:
    - Novel pesticides use at source that can be traced back.
    - Food process by-products repurposed/valorised into new products.

10.2 Systems approach to design of regulation

Food at every stage of the value chain and particularly final products are often the result of convergence of increasingly sophisticated science and technology applications. Therefore, it is strongly advised to develop a systems approach to design of regulation.

This means considering the totality of the processes that lead to a food product, including technologies used in its production and packaging as a whole together with its commercial context, and the broader environmental and societal contexts within which the product will be produced, used and disposed. This is a complex undertaking but increasingly relevant and worthwhile to increase expertise and knowledge towards applied systems thinking in policy design.

Some **examples of complex scenarios** are:

Genomics use in agriculture based on soil microbiome information will likely see agritech companies developing crops that are either resistant to microbiome depleted soil conditions or unfavourable soil microbiomes, or develop fertiliser/pesticide additives that contain genetically modified microorganisms to "restore" depleted soils. Once released into nature, food safety risks as well as complex ecological impacts of such compounds need to be scientifically assessed.

New non-thermal processing raises complex questions that cannot be answered with a linear approach. For example:

- What are the molecular changes to the food material undergoing these processes?
  - What are the changes in nutritional content?
  - Nano particle generation?
  - Toxicity or long-term health effects by other molecular changes such as release of carcinogens?
- Does safety of such technologies at the appliance level in gastronomy and domestic settings differ from large scale industrial applications?

- Does small scale processing have a different effect than large scale processing with these technologies?
- What is the effect of exposure time to the energy source on food material?

Indoor farming: this is another example of the need to rethink regulatory frameworks towards developing a systems approach to regulation design. There is a need to balance drive for innovation towards commercial benefits with understanding the real impact of indoor farming on sustainability and environment:

- Indoor farming is carried out under fully artificial conditions with heavy use of synthetic industrially produced nutrients, potential use of pesticides and antifungals, and in continuous contact with plasticware.
  - Can this be deemed organic?
  - If regulation under industry pressure relaxes definitions of Organic to cover such produce what harm it does to actual organic food industry?
- Is indoor farming actually climate friendly and sustainable?
  - Heavy reliance on mined materials and petrochemicals for machinery and consumables
  - Heavy reliance on energy, even for source of light for photosynthesis

Genomics and Gene Editing with its scientific and regulatory complexities has been touched upon in the first point and it suffices here to say that due to high commercial stakes and high capital costs large corporations will remain the main players in this field. This may make it politically contentious and requires a highly informed regulator to be able to balance the demands of industry for lax regulation with the long-term responsibility towards health and well-being of generations to come. This highlights again that increasingly food regulation is not anymore about a point decision but will impact future generations and geo-environmental processes through time.

10.3 Accelerate regulatory response

As increasingly, technology innovation in general, and so in the food sector, is developed and scaled up with rapid prototyping and quick release of minimally viable prototypes/products onto test markets – time frames from proof of concept to product have become much shorter. This requires not only a more frequent and deeper scanning of the innovation landscape, but also faster regulatory response time frames than in the past. FSA may benefit from following the examples in other countries of regulators engaging proactively with business incubators and venture capital funds to stay abreast of early developments and new emerging technologies, and engage early with researchers and entrepreneurs to help shape the future developments from an early stage. For example, the Dubai Financial Services Authority and their FinTech incubator initiative (DFSA, 2021).

10.4 Manage the digital transition

Digital Technologies, as discussed in section 8 have considerable potential to increase traceability and therefore safety of food production processes and supply chains. Challenges were also identified such as industry-wide implementation of technology hardware and software networks, and risk of data tampering at source, and potential for large-scale mislabelling. However, the main challenge with the fast growth and adoption of these technologies lies in their *systemic effects* which in turn translates into *systemic risks*. Such risks are of an entirely different dimension and require different response models as well as time frames and scale.

As seen in other industries, technology companies rise above regulation access due to the complexity of their technology, business models, operations, the power of their network effects and sheer financial clout. One such seemingly far-fetched example is the Starlink satellite constellation from SpaceX. The terms of use for Starlink satellites puts them under the governance of laws of California, US. However, there is an extra clause in these terms stating that if the reach of the satellites in the future extends to Mars "no earth based government has authority or sovereignty over Martian activities" (Gapper, 2021). Although this may read like science fiction, it illustrates the fact that technology companies already explicitly anticipate it as their right to operate above the law, based on perceived superiority of their technology.

On earthlier matters regulators are finding it very challenging to strike a balance between consumer interests and the free reign of technology companies. This is mainly due to factors such as (Taeihagh et al., 2021):

- Asymmetry in information: Given that most social actors have limited knowledge about how these advanced technologies work, and what their possible applications and the consequences of their deployment are, policy design is inherently impacted by asymmetries in information across agents and at multiple levels of society and government.
- Policy uncertainty: in these sectors policy and regulation design takes place under high levels of uncertainty. This is due to the fact that governments and their respective agencies are often not entirely aware of the nature of the policy problem to be addressed, because generally they do not have the technical skills to understand the complex systems (technical, economic and socio-behavioural) resulting from systemic applications of advanced high-tech technologies.
- Structural power dynamics: deployment of technology impacts different parts of the society differently. Some sectors may benefit disproportionately positively while other sectors may lose out.

10.5 Implications for policy design

Another level of complexity arises when technology, data ownership and synthetic biology converge to dominate food production, distribution, and access. The systemic effects of such convergence can be staggering. This may lead to consolidation of the industry into a few dominant players which might consider themselves as above the law, or on the other hand efforts of small players to carve out a niche remaining below the radar of law. This poses a daunting task for regulators while putting considerable societal responsibility on them, currently not perceived to be part of their remit (Harvard Kennedy School, 2020; James, 2019).

Some of these scenarios are to some extent becoming realities today and are rapidly gaining momentum, and therefore a forward-looking systematic response is required.

To address such arising societal responsibilities relevant to one of the largest global industry complexes, namely the food sector, we would like to suggest three structural approaches:

- Develop procedural policy tools based on a well-informed understanding of these technology fields. This will enable continual monitoring, learning from experience and building expertise. This will also help reduce policy uncertainty over time.
- Principle/value-based regulation, where the regulator's intervention will be focused on guiding towards desired outcomes, rather than detailed and prescriptive rules on how those outcomes must be achieved.
- Building and maintaining a strong network of public interest technologists who could help regulators on high tech matters on demand.

10.6 Summary

It is recommended that FSA considers reimagining their role as a regulatory body and adopting a more proactive anticipatory role in supporting industry to build food safety into its fabric from the start as novel technologies and processes are implemented.

From a regulatory perspective, the scope of food safety will need to be redefined and expanded to encompass systemic risks to human health as well as societal implications of large-scale implementation of novel technologies in the food sector. Therefore, regulators will require in-depth and impartial expertise in order to balance complex supply chains, novel technologies, consumer needs and interest, industry requirements and long-term considerations that will impact future generations and the environment.

The suggested approaches above serve as initial steps to the adoption of a systems approach to policy design that is more in line with the complexities of a technologically networked world.

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