TONY BLAIR INSTITUTE FOR GLOBAL CHANGE

# Technology to Feed the World

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# Contents



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# Executive Summary

The world's population is projected to grow to nearly 10 billion by 2050 – an increase of 2 billion people from today – with the population of sub-Saharan Africa alone expected to double. As governments across the globe grapple with the impacts of climate change and the rise in food insecurity due to Covid-19, an existential question is also coming into focus: How do we prepare now to feed 10 billion people?

Although our current food system fails to meet the needs of people and the planet, there are reasons to be optimistic about the future. Emerging technologies present us with a growing range of opportunities to transform our food and agriculture systems. To harness these opportunities, policymakers, scientists and entrepreneurs must:

- Identify the opportunities these innovations present for health and nutrition, our natural environment and economies.
- Uncover any unintended consequences, trade-offs and gaps in our understanding of these innovations.
- Assess their relative maturity and feasibility, and identify those that hold the most transformative potential.
- Identify barriers, and therefore the questions that need to be answered, to successfully implementing new innovations globally and at scale.

This paper explores these key areas. It illustrates the significant potential of some of the most transformative food and agriculture technologies, while outlining some of the underlying challenges of bringing them to scale responsibly. It also begins to address some policy areas that warrant attention from governments and highlights the questions that we must address to create a food system fit for the 21st century – a system that delivers for everybody, everywhere.

**High-level messages for governments:**

- **Countries should embrace food technologies and seize the economic, environmental and health rewards.**
  Food systems are intimately connected, meaning that by transforming them, we can collectively tackle some of the world's biggest challenges. Food technologies enable us to improve health and nutrition, promote environmental sustainability and deliver economic growth. Governments should seize this significant opportunity.

- **Scaling food technologies requires overcoming several barriers. Governments should lead the**

**effort.**
Technology in itself does not deliver positive change. It’s how we develop and deploy these technologies that matters. There are some key barriers to scaling up food technologies: vested interests, lack of demand, lack of risk capital, infrastructure and inputs such as power, regulatory burdens, and basic science/R&D.

Although overcoming these barriers will require several actors to come together – including innovators, scientists and investors – governments hold significant responsibility for setting the ambition and driving the direction of change. Governments also have a role to play in providing funding, infrastructure and innovative regulation.

- **Governments should act now to save paying the price later.**
  Food systems urgently need reform in the face of climate change, biodiversity loss, food insecurity and deteriorating public health. As this paper sets out, the benefits of scaling up food technologies are clear.

  Transformative technologies in our energy system have been available for years, yet large parts of the world are still reliant on coal. We have been far too slow to deploy clean energy technologies. We can’t afford to make the same mistake with our food systems. It’s not a question of if, but when; at some point trends will force change. Nations with foresight should support the development of the markets of the future.

**Key questions to address:**

As part of this analysis we have identified five sets of questions that provide a starting point for governments that want to grasp the opportunity provided by food technologies. We welcome engagement from all actors interested in helping to address these questions.

- How do we make the unit economics of food technologies work not just in California or the UAE – but globally?
- What is the role for government versus the private sector to drive food tech to scale?
- How can we help farmers adopt these technologies, and make technologies more attractive to retailers and consumers?
- How might employment be affected? How can we make sure we create more winners than losers?
- Which technologies should be prioritised? Can and should multiple technologies work simultaneously, or will some compete with others?

# Introduction: The Need for Another Agricultural Revolution

**We have a significant opportunity to transform our food systems and improve the state of the world in the 21st century.**

Food systems are complex, adaptive systems with many interlinking components. They are vital to the health of human beings, our natural environment and our economies.

In many ways, our global food system is hugely impressive. As the global population has grown, so too has agricultural production. Over the past 50 years, the green revolution has enabled the production of cereal crops to triple with only a relatively small increase in the area of land under cultivation.

We can attribute much of this success to farmers, who have adapted and embraced new technologies. The combine harvester welcomed an era of intensive, industrialised farming – and we have come a long way since its invention in the 1830s.

But today the global food system is also affected by deep inefficiencies, inequalities and externalities. How we grow, process, transport, consume and waste food is damaging both our health and our planet. Food systems already contribute up to 30 per cent of total global emissions, and agricultural land use is the main driver of deforestation. Obesity is on the rise globally, yet at at the same time food insecurity and hunger is increasing. Meanwhile, our soil is degrading at such a rate that we risk losing the world's topsoil within 60 years.

As the population increases, demand for food will continue to grow. And without another agricultural revolution, it is possible that the harmful elements of the food system will inflict increasing amounts of damage.

Fortunately, new technologies and breakthroughs in science offer an opportunity to radically improve our food system.

Scaled up, new food technologies could mean that we can feed more people affordably and healthily, while promoting the health of our planet and preserving natural resources.

But delivering on this future will not be without challenges. And without progressive actions there is a risk that many transformative technologies won't be implemented responsibly or at sufficient pace or scale.

Now is the time to discuss the future of food. Covid-19 has exposed the fragility of food systems all over the world, particularly in developing countries. Sound, responsive and resilient agricultural policies will be vital to "building back better" and achieving net-zero commitments.

The UK will need to think hard about what its food system will look like post-Brexit. Part Two of the National Food Strategy – the first independent review into England's food system in 75 years – is due to be published. The strategy will present a comprehensive plan for transforming the food system, and it is expected to set out how the benefits of the coming revolution in agricultural technology can be maximised. The EU is also striving to develop a food system fit for the 21st century over the next ten years with its Farm to Fork Strategy.

As we set out in our new progressive agenda, now more than ever we need to deliver the practical benefits of new technologies to all people in the ways that matter most. As economies across the globe continue their recoveries from the Covid-19 pandemic, we must evaluate the technologies that have the most potential. We can then accelerate their deployment, bringing them to scale responsibly. The countries that successfully grasp these opportunities can lead the world in the future of food.

# An Opportunity to Transform Our Food Systems

There is a broad consensus on what we want our food systems to do: deliver enough affordable and nutritious food to every person in the world, within planetary constraints and without jeopardising future generations and the environment, while providing economic opportunities.

Our food system has the potential to provide increased choice, with high nutritional value, so people can live long and healthy lives. It can provide jobs and incomes fit for both the developed and developing world. It can also work to promote biodiversity and preserve natural resources, and – unlike other sectors – it can actively remove emissions from the atmosphere and reduce the damage caused by climate change. By doing so it can provide food security for every person in every country.

## Food System Opportunities vs. Where We Are Now

Although the global food system has demonstrated a remarkable ability to adapt over time, the way we currently produce and consume food fails to deliver to its full potential. Table 1 compares the opportunities presented by the food system to the current reality.

**Table 1 – Food system goals and objectives vs. current state of play**

| Goals | Objectives | Where We Are Now |
|---|---|---|
| **Provide proper health and nutrition** | Little or no obesity or malnutrition | • In 2019, 21.3 per cent of children under the age of 5 were stunted, and 5.6 per cent were overweight.<br>• Adult obesity is on the rise in all regions.<br>• Hundreds of millions of people face health challenges – including obesity, diabetes and heart disease – linked to unhealthy diets. |
| | Provide enough affordable food for | • For decades, food insecurity was in decline.<br>• However, it has increased since 2015.<br>• More than 1.5 billion people cannot afford a diet that meets the required levels of essential nutrients. |

| Goals | Objectives | Where We Are Now |
|---|---|---|
| | everybody, everywhere (food security) | • Nearly 690 million – 8.9 per cent of the world population – people are hungry.<br>• It's estimated that healthy diets are unaffordable for more than 3 billion people in the world. |
| | Provide safe and uncontaminated food | • 80 per cent of antibiotics in the US are used for farm animals.<br>• The WHO estimates that one in ten people fall ill every year from eating contaminated food. |
| | Offer increased diversity of food, better quality and choice | • More than half of the global energy need is currently met by only four crops: rice, potatoes, wheat and maize. |
| **Deliver economic opportunities and growth** | Provide secure jobs and resilient incomes fit for the modern world | • Agriculture is the single-largest employer in the world.<br>• Small-scale farmers make up a majority of the world's poor and live, on average, on less than $2 a day.<br>• Farmers end up with only a small portion of the final consumer price. The majority of profit is made on other continents. |
| | Promote economic growth in the developed and developing world | • Over the past 20 years, trade in agricultural products has more than tripled to reach $1.33 trillion, driven mostly by demand growth in emerging economies and greater south-south trade. |

| Goals | Objectives | Where We Are Now |
|---|---|---|
| | Improve efficiency and minimise loss and waste | • 33 per cent of food goes to waste.<br>• In the US alone, 31 to 40 per cent of post-harvest food supply is lost or wasted, at a cost of $160 billion annually. |
| | Minimise economic inefficiencies and externalities | • The hidden costs of global food and land-use systems amount to $12 trillion, compared to the $10 trillion market value of the global food system.<br>• If current consumption patterns continue, diet-related health costs linked to mortality and diet-related non-communicable disease are projected to exceed $1.3 trillion per year by 2030.<br>• The diet-related social cost of greenhouse gas emissions associated with current dietary patterns is estimated to reach more than $1.7 trillion per year by 2030. |
| **Promote environmental sustainability** | Promote biodiversity | • Agricultural land use dominates 40 per cent of the earth's surface and is the main driver of deforestation.<br>• The widespread and inefficient use of agrichemicals like pesticides has adversely affected biodiversity.<br>• The UN states that around 1 million animal and plant species are now threatened with extinction. |
| | Reduce emissions and the threats posed by climate change | • Food and land-use systems cause up to 30 per cent of total greenhouse gas emissions.<br>• Based on current trends, the agri-food sector is expected to produce half of all greenhouse gas emissions by 2050. |

| Goals | Objectives | Where We Are Now |
|---|---|---|
| | Preserve natural resources such as water and soil health | • According to the UN's Food and Agricultural Organisation, a third of the world's soil is now moderately to highly degraded.<br>• Soils are declining in productivity through poor agronomic practices, including continual mining of the soil without fertiliser or compost or other resources to replace it.<br>• According to the UN, food production accounts for 40 per cent of land use and 70 per cent of freshwater consumption.<br>• By 2030, the world may face a 40 per cent water supply-demand gap.<br>• NASA reports that the majority of the world's fresh-water supplies are draining faster than they are being replenished. Fresh-water demand is set to increase by 55 per cent by 2050. |
| | Increase resilience to threats posed by climate change and environmental degradation | • Climate change is already undermining crop yield in some areas. This is expected to continue and accelerate.<br>• Based on current trends, climate change could force over 100 million people into extreme poverty by 2030, mostly through impacts on agriculture and food security. |

## Connections and Conflicts Across Objectives in the Food System

The global food system has many interdependent and interconnected features, and therefore represents a complex policy space. But it also offers an opportunity to make multiple improvements at once.

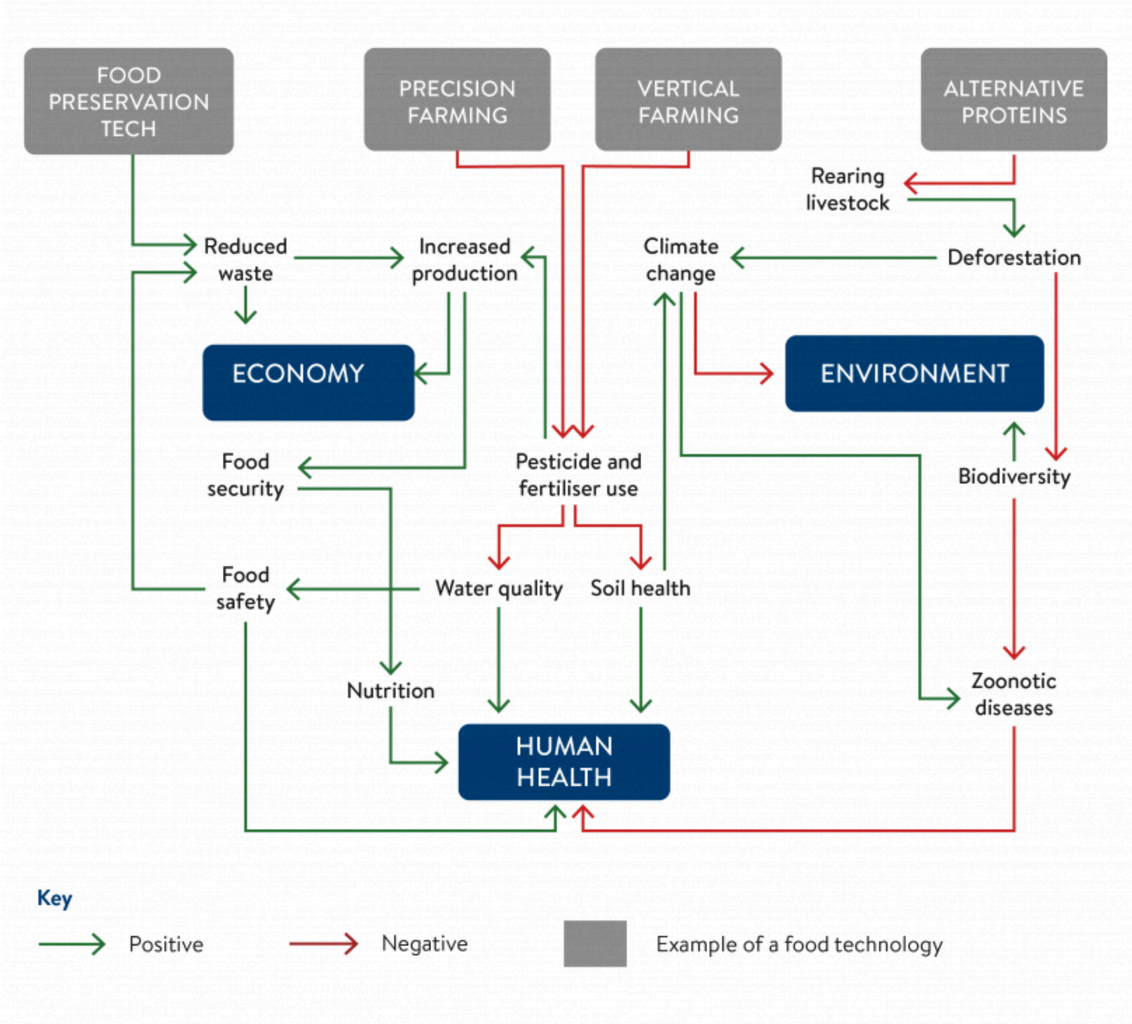
Many of the goals outlined in Table 1 (across the areas of economy, health and environmental sustainability) are intimately linked. As a result, for some goals, it will be possible for policymakers to successfully tackle them in tandem. Other goals are in tension, meaning fixing one could make another worse.

The interconnected nature and complexity of the food system highlights the need to take a systems approach to food policy, where any intervention or innovation is evaluated across multiple elements. Food and agritech is relevant to health, nutrition, climate change, biodiversity, jobs and trade. We must avoid policy formulation that takes place in silos.

Typically, food systems have been evaluated based on yield. But a focus purely on productivity has come at the expense of the natural environment and human health.

For example, Figure 2 shows that an increase in the use of fertilisers and pesticides leads to increased production, food security and economic gain for farmers. However, if used irresponsibly these agricultural chemicals also damage soil health, contribute to climate change and have a negative impact on the nutritional value of foods. Climate change is and will continue to affect global food security. It also increases the likelihood of zoonotic diseases such as Covid-19 which – as we have seen – have disastrous impacts on human health and economies.

**Figure 1 – Mapping some key relationships between food technologies and policy objectives**




*Source: TBI team analysis. Positive link polarity means the impacted variable moves in the same direction as the driving variable (e.g. increased pesticide and fertiliser use will increase production). Negative link polarity indicates that the impacted variable moves in the opposite direction (e.g. policies supporting alternative proteins will decrease the rearing of livestock).*

We also need to take a long-term view of the food system. Building a food system that provides strong economic growth and jobs now, but perhaps at the expense of environmental sustainability, will be useless when climate change threatens jobs, economic growth and ultimately food security in years to come.

Fortunately, whereas previous farming approaches – such as mechanisation and the use of fertilisers – have encouraged positive impacts on some aspects of the food system at the expense of others, new and emerging food and agriculture innovations can potentially create valuable co-benefits.

The next section discusses the opportunity presented by a range of innovations across the food system.

# Innovation Is an Effective Route to Change

This section explores the opportunities and challenges stemming from the food-technology revolution. It considers how these technologies come together to deliver innovations that can have a positive impact on the environment, human health and the economy. It then discusses some key areas that warrant attention from policymakers, while recognising that progress will – to some extent – be driven by the private sector.

Although this paper has a global scope, it does not suggest that every innovation will be feasible, or is even desirable, on a global scale. Different countries have different natural environments, as well as different social, economic and political landscapes; some technologies will therefore be better suited than others to specific local contexts.

In developing countries and emerging economies, there is huge scope for change. Many of these countries have an opportunity to leapfrog the unsustainable methods of food production adopted in the Western world, and instead adopt revolutionary technologies in a relatively short period of time.

## Key Technologies

Despite the overwhelming set of challenges posed by our food system, the opportunity for change is strong. Innovations in food and agriculture provide some of the best and most feasible ways to solve many of the world's toughest challenges at once.

Technology offers a chance to make our food system more resilient, more sustainable and better for both people and the planet. It's also likely that scaling up food technologies will create new economic opportunities, while reducing negative economic and environmental externalities. Crucially, many of these innovations enable us to make dramatic improvements to the food system without asking individuals to make unrealistic sacrifices.

For example, precision farming and artificial intelligence (AI) solutions can maximise crop yields. Technologies can help livestock emit less methane, and plant-based and lab-grown foods enable us to produce protein products with far less strain on resources than conventional animal proteins. Vertical farms can help us produce more food with less land, less water and no harmful pesticides, and drone technology and satellites allow farmers to evaluate crop conditions and reduce reliance on harmful fertilisers. Breakthroughs in science and new seed and soil technologies can help to regenerate the soil, to capture more carbon and to improve the nutritional value of foods.

Progress across these innovation areas has been driven by the development of several digital and biological cross-cutting technologies, including but not limited to:

- **Robotics and drones:** Robotics refers to the design, manufacture, and use of robots for personal and commercial use. Drones are unmanned aerial vehicles (UAVs).
- **Nanotechnology:** Science, engineering and technology conducted at the nanoscale, or the study and application of extremely small things.
- **Synthetic biology:** A field of science that involves redesigning organisms for useful purposes by engineering them to have new abilities. Researchers are harnessing the power of synthetic biology to solve problems in medicine, manufacturing and agriculture.
- **Cellular agriculture:** The production of agricultural products from cell cultures using biotechnology, tissue engineering, molecular biology and synthetic biology.
- **Gene-editing technology:** A group of technologies that give scientists the ability to edit an organism's DNA. CRISPR is the most commonly used technology to edit genes.
- **Artificial intelligence (AI):** Computers that can recognise complex patterns, process information, draw conclusions and make recommendations.
- **Computer vision:** A field of AI that trains computers to interpret and understand the visual world.
- **Blockchain:** A secure, decentralised and transparent way of recording and sharing data, with no need to rely on third-part intermediaries.
- **Machine learning:** An application of artificial intelligence that provides systems with the ability to automatically learn and improve from experience without being explicitly programmed.
- **Internet of Things (IoT):** Describes the idea of everyday items – from medical wearables that monitor users' physical condition to cars and tracking devices inserted into parcels – being connected to the internet and identifiable by other devices.
- **3D printing:** Allows manufacturing businesses to print their own parts, with less tooling, at a lower cost and faster than traditional processes.
- **Virtual reality (VR):** Offers immersive digital experiences that simulate the real world.

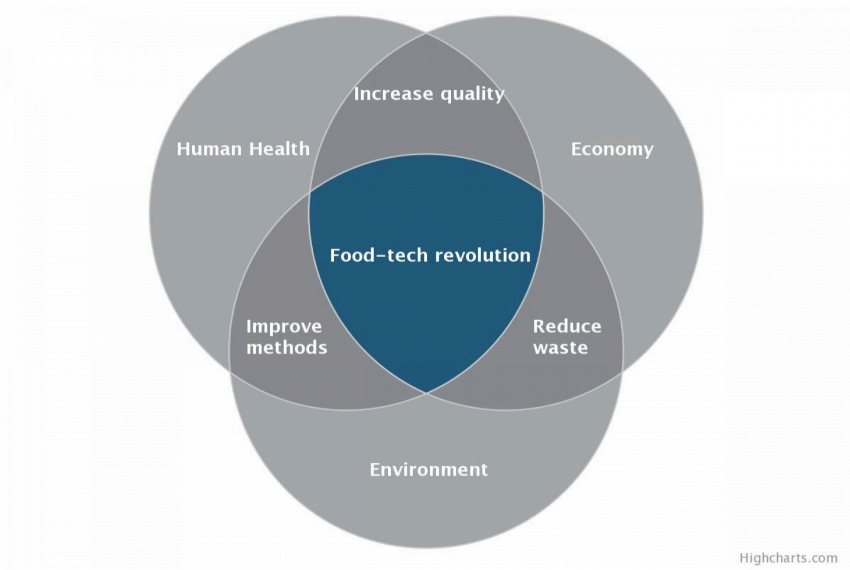
## The Food-Tech Revolution

Innovation in food systems should take place with three main policy goals in mind:

1. Providing proper health and nutrition.
2. Delivering economic opportunities and growth.
3. Promoting environmental sustainability.

Policies or innovations that aim to address one aspect of the system are likely to produce impacts elsewhere. Going forward, any new solution or innovation must strive to balance these policy goals or, at the very least, not promote one at great expense to another.

**Figure 2 – Goals framework for the food-tech revolution**




In our analysis and goals framework, we have identified three main categories of innovation for the 21st-century food-tech revolution – enabled by the application of software and data – that collectively contribute to achieving these policy goals. They are:

1. **Innovations that can increase the quality of foods and farming.** Whereas innovations during the green revolution enabled farmers to produce larger quantities of food with less land, new innovations enable us to increase the quality of foods and farming. Precision-farming technologies and advances in biotechnology mean we can reduce reliance on agrichemicals, improve soil quality and make foods more nutritious. This means we can still get more from our food system with fewer inputs, but with less strain on the world's natural resources.
2. **Innovations that can improve methods for producing food.** Completely novel methods of producing food – which take production away from farms and towards more controlled environments and labs – now exist. Innovations such as vertical farming and alternative proteins offer radical alternatives to traditional production methods, and hold significant opportunities for the environment, nutrition and health. Former Google CEO Eric Schmidt has gone as far to say that plant-based meat is the number-one tech trend that will significantly improve the world.
3. **Innovations that can reduce waste.** Around one-third of all food produced gets lost or wasted each year. In sub-Saharan Africa, somewhere between 30 and 60 per cent of food that is grown never reaches the plates of consumers – a bleak statistic, especially when considering that so many people suffer from hunger and nutrient deficiencies. Mobile technologies and digital marketplaces can help connect actors across the system to reduce losses, while smart packaging and food-sensing

technologies can help food stay fresher for longer. A circular-economy approach can ensure that by-products and waste from food systems can be repurposed and used in much higher-value products. The use of food waste as feedstock for anaerobic digestion is preferable to dumping waste in landfill, which results in methane emissions – one of the most damaging greenhouse gases driving climate change. However, this approach does not address the root cause of the problem – i.e. producing too much food in the wrong place at the wrong time.

We have also identified 12 specific innovations within these categories, which are summarised below in Table 2. Many of these innovations combine several of the cross-cutting technologies introduced above. Like Tesla – which didn't invent the car, but instead improved and integrated existing technologies – startups in the food system are combining technologies to create impactful innovations. For example, vertical farms combine robotics, artificial intelligence and machine learning, the IoT, synthetic biology and gene editing.

**Table 2 – Three categories of food-tech innovation and individual innovations within each**

| A. Increase quality | B. Improve methods | C. Reduce waste |
|---|---|---|
| **Precision** | **New Foods** | **Supply Chain** |
| • Robotics and automation<br>• Farm-management software and sensing | • Plant-based food alternatives<br>• Cultured and lab-grown food | • Food sensing and processing<br>• Food preservation and smart packaging<br>• Renewable cold-storage |
| **Protection** | **New Farms** | **Marketplaces / mobile services** |
| • Gene editing<br>• Microbiome | • Controlled environment agriculture and vertical farms | • Digital marketplaces |

technologies for crops and soil
- Biological-based crop protection

Although this list is not exhaustive, it aims to illustrate the transformative potential of innovations in food and agriculture across the supply chain. It's also important to note that although many of these innovations offer significant opportunities to improve the way we produce, distribute and consume food, many are in their early phases; in some cases further research is needed to identify their true potential, as well as any unintended consequences they may bring. No one technology presents a single perfect solution. The task for policymakers is to work out how to make the most suitable technologies work to achieve the greatest impact, while minimising any risks.

The following section highlights the strengths of each of these innovations to deliver against the three policy goals. It also considers any weaknesses as well as future opportunities and challenges they present.

## Food and Agriculture Innovations: The Current State of Play

Building the best possible future food system is likely to require embracing some, if not all, of these innovations. But there are challenges to maximising their potential. The risks that come with scaling up these technologies must be addressed to enable positive impact across policy goals.

First and foremost, we must ensure that proper scientific research is conducted. And we must consider the impact that new technologies could have on our food system today, as well as the impact that they could have for years to come. There may be some unforeseen outcomes that we should attempt to anticipate now.

Table 3 summarises some of the wider impacts of these innovations. The questions we consider include:

- What are the key strengths of the innovation area?
- What are the current limitations?
- What opportunities could be created if this technology was scaled up? What opportunities are there to advance this area of innovation further and how could this have a greater impact?
- What are the possible negative implications of scaling the technology up further? What are the trade-offs?

## Table 3 – State of play for innovations

| | | EXISTING TECHNOLOGIES AND APPROACHES | | LOOKING AHEAD | |
|---|---|---|---|---|---|
| **CATEGORY** | **DESCRIPTION** | **STRENGTHS** | **WEAKNESSES** | **OPPORTUNITIES** | **THREATS/RISKS** |
| **A. Increase Quality** | **Precision:** Data-driven decision-making enables farmers to optimise and apply inputs with precision – using drones, satellites, sensors and other technologies | • Increased productivity, reduced farm operating costs<br>• Fewer inputs like water, energy and chemicals means better environmental outcomes and improved soil health | • Poor connectivity stifles progress<br>• High initial capital cost<br>• Technologies come with steep learning curve for users<br>• Closed systems and limited data | • Help improve outcomes on smaller farms and in developing countries<br>• Apply more advanced sensor technologies and more autonomous systems to more crops | • Farms may not require human labour<br>• May exclude smaller farms<br>• Loss or misuse of data could result in financial and environmental losses<br>• May lead to a loss of farmer know-how |
| | **Protection:** Advances in biotech such as gene-editing, soil microbiome technologies and biological-based crop protection can protect crops and improve soil health | • Improved functional benefits of produce, increased resilience and productivity, and improved nutrition<br>• Reduced chemical intervention means better soil health, fewer emissions | • Development can be lengthy<br>• Applications often have to be developed to meet specific needs and regional characteristics<br>• Microbiome research at an early stage | • Further advances in understanding of microbiome could enable us to improve soil and human health<br>• Increased resistance to future threats such as climate change | • Could result in less biodiversity<br>• Ethical concerns<br>• Unpredictable impact on human health<br>• Regulation could hinder progress |
| **B. Improve Methods** | **New foods:** Plant-based proteins and lab-grown and synthetic foods such as cultured meat and novel ingredients | • Less prone to biological risk or disease<br>• Lower threat of antibiotic resistance<br>• Significantly lower environmental impact: reduced water use, land use and fewer emissions | • Cultured meat not yet commercialised<br>• Cultured-meat production requires overcoming technology hurdles<br>• Consumer acceptance is still low on a global scale | • Free up land mass and increase biodiversity, greater food security<br>• Decreased threat of antibiotic resistance, reduced disease threat<br>• Opportunity to make more foods in labs | • Could lead to loss of livelihoods for countries dependent on livestock<br>• Monocultures could negatively affect soil and biodiversity<br>• Health impacts not fully known |
| | **New farms:** Food grown in indoor, highly controlled environments usually in urban areas, such as vertical farms | • Eliminates the need for harmful chemicals<br>• Fewer inputs and less land required<br>• Shorter supply-chains | • Requires large amounts of energy<br>• Unit economics remains uncertain, cost of artificial lighting is particularly high<br>• Only currently suited to certain crops | • Protection from climate threats and increased food security<br>• Ideal growing conditions could produce healthier and more nutritious produce<br>• Increased range of foods produced | • No export model for vertical farming<br>• Maximum production potential remains to be confirmed experimentally<br>• Need further evidence on significance of soil to human health |
| **C. Reduce Waste** | **Supply Chain:** Food-processing and inspection tech, cold-storage and preservation tech including smart packaging solutions and nanotechnologies | • Can keep food fresher for longer<br>• Increased traceability, reduced waste, increased food security<br>• Reduced financial losses for producers and consumers | • Food preservation tech only applicable to certain foods<br>• Many components in smart packaging are not completely sustainable | • Consumer demand for greater transparency and freshness<br>• Reduce impact from food safety issues with further innovations like automated foreign object detection | • Cybersecurity and data-privacy issues<br>• Lack of knowledge among food producers on how to integrate these technologies<br>• Safety concerns re. nanotechnologies |
| | **Marketplaces/mobile services:** Better procurement processes and price transparency, trading platforms to facilitate distribution of food and equipment | • Addresses distribution challenges<br>• Increased food security in vulnerable areas<br>• Increased financial inclusion for farmers and access to new markets | • Poor connectivity in some areas stifles progress<br>• Poor knowledge of digital technologies prevents uptake | • Blockchain agriculture, to attain provenance and traceability of food, is expected to grow in importance<br>• Economic opportunities in developing countries | • Areas lacking basic agricultural infrastructure and data availability could be left out |

*View a full screen, accessible version of this table*

*A more detailed analysis of the innovations can be found in the annex*

Each of the innovation areas set out in Table 3 has its own strengths and weaknesses and presents both opportunities and risks. We have identified some areas within Table 3 (highlighted in red) that warrant attention from policymakers. These areas are discussed in more detail in the next section.

## A Deep Dive Into Innovations: Opportunities and Challenges for Policy

### Precision: Strengths

Precision agriculture is an approach to farm management that uses technology to ensure that crops – at a subfield or even individual plant level – and soil receive exactly what they need for optimum health and productivity. For example, satellite imagery and sensors can help pinpoint the exact amount of fertiliser and water needed by a crop and link equipment that is designed to apply variable rates of inputs. Specialised agribots can tend to crops – taking care of weeding, fertilising and harvesting. This approach is made possible by the revolution in data available to the farmer.

The concept of precision agriculture has been around for a while, and although advances in technology present significant opportunities to come, technologies exist today that can deliver significant benefits across policy goals. Compared to other technologies, the trade-offs and unintended consequences are limited. Precision-farming techniques stand to benefit every farm in every country.

- **Environment:** More precise and accurate farming methods can lead to more accurate selection and breeding of varieties and species, and better application of inputs such as water, crop protection and fertilisers. In turn this can help to reduce inefficiencies and waste and save scarce resources. Precision-farming methods also offer an opportunity to regenerate the soil through reduced use of harmful chemicals and mechanisation. For example, robots allow re-aeration of the soil when they replace traditional heavy tractors, which reduces soil erosion.
- **Health:** Increasing evidence shows that declining soil health is also directly affecting human health, and as precision agriculture can help regenerate the soil, it can also help to increase the nutritional value of foods. Soil fertility is directly correlated with the nutrient content of food crops, and over the past 50 years there has been a significant decline in the amounts of protein, calcium, iron, riboflavin and vitamin C in conventionally grown fruits and vegetables. Humans require around 60 minerals for optimal health, but only eight minerals are available in a meaningful quantity in most of the food we eat today. Precision agriculture can also have positive impacts on health by contributing to both food security and safety as a result of increased productivity and using fewer harmful chemicals.
- **Economy:** Given the small amount that farmers receive for their products, many see cost-reduction and more intensive farming methods as the only way to run their businesses profitably. Using precision-farming technologies to guide farmers' use of inputs and tools enables them to significantly increase productivity, reduce farm operating costs and save time, while also farming more sustainably. Nesta has predicted that precision-farming methods could increase the income of an average farm by 20 per cent in the UK. Small family-run farms in particular stand to benefit. Automation can also help with a declining and ageing workforce in the farming sector (the average age of a UK farmer is 58, while in Japan it is around 70).

**Precision: Weaknesses**

**The data challenge:** Modern farms can collect a potentially huge amount of data. For example, sensors can measure many variables such as moisture levels in the soil, while weather data can be obtained from weather stations. Used effectively, data can offer valuable insights and help farmers make important decisions, such as when to spray fertiliser. The challenge is putting this data to good use by interpreting it properly and using it to create useful insights for farmers.

Here we point out three key factors holding back the effective use of data in farming: interoperability standards, ownership and security, and bandwidth constraints. Policymakers have a role to play in terms of setting and supporting appropriate data infrastructure and standards.

- Interoperability standards: To be most useful, data from multiple sources including public data, machine and sensor data, and other privately held data needs to be integrated. Yet too often smart farming systems and machinery lack interoperability. This means farmers have to manually input data, which in turn prevents valuable production gains.
- Ownership and security: Currently, a lack of transparency and clarity around issues such as data ownership and sovereignty, as well as privacy, means that many farmers are reluctant to share data, and countries seek to maintain local data hosting. Most of the useful farm data produced is currently in the hands of the private sector, meaning there is a risk companies could decide to take potentially market-distorting actions. The role of government is to make sure that data sharing happens in a way that increases efficiency and equity.
- Bandwidth constraints: Farming is currently a distinctly rural enterprise, and many rural areas still lack access to the internet and power. Taking digital farming mainstream will require more energy, faster networks, and strong and reliable internet signals.

**Lack of knowledge and capital:** Precision-farming methods are also often constrained by capital and the knowledge/skills required to operate the technology. Farmers require training to embrace even simple sensor, drone and satellite technologies. This is partly why uptake of precision-farming technologies has been low, despite the economic benefits for farmers. For example, in parts of Africa, lower rates of literacy have meant that technology has caught on more slowly.

> **Key takeaways for policymakers:**
>
> - Precision-farming technologies that exist today have the potential to deliver significant benefits in both developed and developing countries.
> - Precision-agriculture technologies represent a missed opportunity in many countries. Governments can support precision-farming practices and tools to make their economies more resilient post Covid-19.
> - Many precision-farming technologies are already on the market. But asking farmers to adopt new techniques requires capital for equipment, training, new infrastructure and improved compatibility between hardware and software. Policymakers will need to consider how to effectively support this transition.

**Protection: Threats/Risks**

Innovations in seeds, fertilisers and crop protection have multiple benefits. For example, gene editing presents new opportunities for the way crops are produced and improved – it has the potential to boost yields, increase disease resistance, improve taste and nutritional value, and tackle allergens. Unlike genetic modification, gene editing is based on a natural process.

Biological-based crop protection can eliminate pests while addressing the environmental challenges of using chemicals. Harnessing the plant and soil microbiome through technologies and smarter micro treatments could potentially revolutionise agriculture by increasing productivity, quality, and improving environmental outcomes.

However, food and agriculture protection technologies also raise some challenges and risks that policymakers should engage with now.

**The challenges facing microbiome technologies:** Microbes play a beneficial role in agricultural environments. For example, they can turn nitrogen from the air into soluble nitrates that can act as natural fertiliser. Advances in agricultural biotechnology are helping us to understand and exploit these microbes for beneficial outcomes. We may, for example, be able to reduce the use of chemicals in farming and increase sustainable production. Indigo Ag's technology identifies beneficial microbes and combines them to develop seed treaters. This means crops are better protected and can withstand harsh environments.

However, although there has been an enormous leap in microbiome research – enabled by rapid-sequencing technologies – and some of this has resulted in practical innovations, research is still at an early stage.

New approaches being explored include managing environmental conditions to promote microbiome diversity, using synthetic biology to design microbiomes with a particular function, and developing diagnostics, predictive models and biomarkers with applications like monitoring the health of water sources and soil. Harnessing the growing body of knowledge on microbiomes is expected to generate new ways to revolutionise agriculture, such as increasing nutrient availability and improving soil structure. However, microbiomes are extremely complicated, and complex interactions occur between and within microbiomes and their hosts and environments. As a result, limited research has been translated into new ideas and practical solutions for farmers. A key challenge for research is to understand the communication molecules used by plants or microbes. There is also a need for more progress in the methods used to analyse ecological conditions.

There have been some moves in the right direction by governments. In 2016, the White House launched the US microbiome initiative to enhance innovation and commercialisation, of which crop and soil microbiomes are a core component. The EU Commission launched the Bioeconomy Forum in 2016, and harnessing microbiomes for food and nutritional security is a key programme topic.

**Confronting the risks of gene editing:** Gene editing involves making slight changes to a plant's existing genes and is considered by many scientists to be as safe as traditional plant-breeding techniques. CRISPR is one type of gene-editing technology that holds great potential. Gene editing through CRISPR can help increase yield, improve the nutritional value of crops and increase resilience to extreme weather patterns.

Gene editing differs from genetic modification (GM), which has previously received backlash from consumers. It is widely accepted that gene editing through CRISPR is cheaper, faster, simpler and safer than GM technology. Table 4 provides a comparison of the two techniques.

However, any technology that interferes with nature is not completely immune from unintended consequences, and gene editing has raised environmental, human health and ethical concerns. Some researchers claim that new genetic-engineering techniques such as CRISPR could cause "genetic havoc".

As a result, some experts have argued that gene editing in the US has escaped necessary regulation. On the other hand, the EU's high court ruled that gene-edited plants should be regulated in the same way as GMOs were in 2018, causing confusion among many plant scientists. But the EU's new Farm to Fork Strategy acknowledges that new biotechnologies may play a role in increasing sustainability and states that, in response to requests from member states, the Commission will look into the benefits of new genomic techniques.

Despite all this, there are now over a million geneticists worldwide working with CRISPR technology, and it's essential that the right kind of regulation keeps pace with developments in the technology. Rather than updating or adapting existing, outdated regulations, regulators should consider starting fresh to design regulation that is truly fit for 21st-century technologies like gene editing.

**Table 4 – A comparison between GMOs and gene editing**

| | Gene editing | GMOs |
|---|---|---|
| **Process** | • Involves making slight changes to existing genes in a plant or animal (just a few DNA letters)<br>• Doesn't transfer genes from one organisism to another | • Involves transfer of entire genes or groups of genes from one species to another<br>• This artificial manipulation would not happen in nature |

| | | |
|---|---|---|
| **Advantages** | • CRISPR is cheaper, more precision and faster than traditional genetic modification | • N/A |
| **Safety implications** | • Considered to be safe, as it imitates the process of mutation on which crop breeding has always depended<br>• Could pose a threat if used irresponsibly | • Many GM foods are on the market, having deemed to be safe by regulators. However, public perception remains a barrier to acceptance. |
| **Ethical implications** | • The same technologies used to create gene-edited foods could be used for ither potentially damaging uses | • Can disrupt natural biodiversity and impact ecosystems |

*Source: Team Analysis, National Geographic*

**Key takeaways for policymakers:**

- Microbiome technologies could hold enormous potential and therefore warrant more research. Links will need to be made between different disciplines such as food, agriculture, the environment, health and research, and policymaking must take a joined-up approach.
- It's crucial that research and regulations keep pace with developments in genetic engineering. More research is needed to understand the implications of both CRISPR and other engineering techniques.
- Public acceptance will be key to the success of crop-protection technologies. GM foods became an object of controversy in both the EU and US and new food protection technologies could raise similar concerns. The risks need to be properly assessed and regulation needs to be approached with absolute transparency to avoid public backlash.

### New Farms: Weaknesses

Vertical farming involves growing crops in vertically stacked layers in an indoor environment under carefully controlled conditions. Vertical farms require a range of technologies to function, such as LEDs, rotating beds, ventilation systems, cameras and sensors, and automated and autonomous mechatronics.

Vertical farming has multiple advantages: It means more can be produced in less space; it offers a means of guaranteeing yield irrespective of the weather; it significantly reduces the inputs required (such as fertilisers, pesticides and water); and it doesn't disturb animals and trees, so is better for biodiversity. Some vertical-farming companies claim food can be produced with better nutritional value. Vertical farming makes it possible to grow food within a short distance of where it is consumed, reducing the distance needed to get the food from "farm to plate" and reducing its carbon footprint.

However, in its current form, vertical farming also has some weaknesses:

- **It requires large amounts of energy:** Although vertical farming uses less water and fewer nutrients than traditional farming, it is very energy intensive, largely due to the use of supplementary lights like LEDs, and climate control. It's estimated that vertical farming takes between 20 and 176 kWh per kg or more to grow crops than in greenhouses. If this energy doesn't come from renewable sources, vertical farming could have a negative environmental impact.
- **The unit economics remains uncertain:** Some have questioned the commercial viability of vertical farming on a large scale. The start-up costs are incredibly high compared to traditional farming, and the current cost of providing lighting, heating, water and labour could outweigh the benefits from the output. As a result, vertical farms to date have been most effective at growing leafy vegetables and high-value herbs. Slower-growing vegetables are not yet profitable in a vertical farming system.

However, it's likely that innovations in the infrastructure (like automation, lighting and temperature controls) could bring down the power and space costs. Or – as the companies Bayer and Temasek are doing – it's possible to upgrade the "software" (or the biology of the crops) with tools like CRISPR, so they are more successful in vertical-farming environments.

The venture-capital model is unlikely to be sufficient to fund vertical farming on a large scale. To scale up vertical farms so they can produce significantly increased output, the capital expenditure will be enormous. Governments are likely to need to play a major role in supporting the infrastructure required to make vertical farming feasible at scale.

> **Key takeaways for policymakers:**
>
> - More research and data are needed to assess the feasibility of vertical farming as well as its ability to sustainably feed the world at scale. In particular, we should consider how much energy consumption is required to run vertical farms in different locations and how the environmental impacts compare to traditional farming methods.

- Policymakers should consider what new technologies are needed to make vertical farming economically viable, and whether the benefits of this method could justify large-scale government support in the form of funding and infrastructure.
- As vertical farms are likely to be placed in cities, countries should think about how they might be integrated into urban planning, how to ensure inclusiveness and what their impact might be on rural food supply chains.

**New Foods: Opportunities**

The production and consumption of animal products (mainly meat) has an enormous impact on the environment. Academic analysis shows it will be impossible for a global population of 10 billion to consume the amount and type of protein typical of current diets in North America and Europe if we want to achieve the UN Sustainable Development Goals (SDGs) and meet the requirements set out in the Paris Agreement on climate change.

As a result, experts have advocated for a major shift in global diets away from meat and dairy. Yet although sustainable diets are on the rise in parts of the developed world, the global consumption of meat is expected to increase as the global population grows and people in developing countries move up the income ladder. Addressing this through policy is a key necessity to reverse the trend across all continents.

However, even if it is desirable, it is not realistic to expect the whole world to radically change their diets. What we can do is radically change the way protein is produced to address the soaring demand for affordable, high-quality proteins without the high environmental cost. This is what several innovative companies are doing by developing alternative protein sources.

There are different types of alternative proteins:

- **Plant protein** is the most well-established alternative protein category.
- **Insect protein** has been hailed as an environmentally friendly, alternative protein source.
- **Cultured or cultivated meat** is animal meat that is produced by growing cells outside the bodies of animals. It's not yet on the market but could reach the high-end market over the next five years.
- **Lab-grown foods/ingredients and precision fermentation** enable the programming of microorganisms to produce complex organic molecules such as proteins.

In 2019, the market base for alternative protein was approximately $2.2 billion compared with a global meat market of $1.7 trillion. Alternative proteins are likely to have to be competitive in price, taste and convenience before they can compete with conventionally produced animal protein. But if scaled up, alternative proteins present an opportunity to solve some of the world's most pressing challenges. These include:

- **Improving environmental outcomes and reducing the threats posed by climate change:** Livestock accounts for around 15 per cent of greenhouse gas emissions and use more than one-quarter of the planet's ice-free surface. A recent report showed that the biggest dairy companies in the world have the same combined greenhouse gas emissions as the UK. Studies show that replacing conventional meat with plant-based meat substantially reduced every environmental impact measured. The Good Food Institute states that plant-based meat uses 47 to 99 per cent less land, it emits 30 to 90 per cent less greenhouse gas, uses 72 to 99 per cent less water, and causes 51 to 91 per cent less aquatic nutrient pollution. As it requires fewer natural resources than conventional meat, a move to alternative proteins also reduces deforestation and biodiversity loss.

Alternative proteins can also act as feedstock for livestock or fish. Worldwide, currently 35 per cent of crop production is allocated to animal feed. In developed countries, this figure is nearly 60 per cent. Using land in this way is extremely inefficient; for every 100 calories of grain we feed animals, we only get 12 calories of chicken, or 3 calories of beef. Farming insects is also a beneficial alternative for animal feed: It is estimated that it requires 50 to 90 per cent less land than conventional agriculture per kilogram of protein and could reduce greenhouse gas emissions from the livestock industry by 50 per cent by 2050.

Insects can also be served as human food, and can feed on food waste, although there is still some work to be done on insects for human consumption at a policy level. UK-based startup Better Origin has created a technology that converts insects into viable products – known as insect-based bioconversion. It tackles the twin challenges of food security and waste, and cuts carbon emissions.

- **Improving nutrition:** Protein is an essential component of a nutritious diet, yet a large percentage of the global population is either malnourished or obese/overweight. In August 2020, the Stanford University School of Medicine published the first significant study to directly compare the nutritional value of plant-based meat to animal-based meat. It found that consuming plant-based meat led to a statistically significant positive impact on bad cholesterol and weight.
- **Mitigating the rise of antibiotic-resistant infections:** Antibiotic resistance is one of the most critical health concerns of our time. One of the main causes of antibiotic resistance is the rise in antibiotics being given to animals slaughtered for food. For example, in the US, more than 70 per cent of medically relevant antibiotics are used in animal agriculture. Antibiotics can cause bacteria to adapt and become resistant, which also affects human medicine. Plant-based and lab-grown proteins require no antibiotics, so minimise this impact.
- **Increasing food security:** Covid-19 has exposed the vulnerabilities of our current food system. Alternative proteins can help create a supply chain that is much more secure, efficient and resilient. Furthermore, as the rate of innovation in the alternative-protein sector increases, these products will become more accessible to emerging markets such as Africa and can continue to provide a cheaper

alternative to traditional protein sources.

- **Creating new jobs in the green industry:** There are clear economic incentives for countries that encourage innovation in the alternative protein market: New market opportunities will arise, and new jobs will be created. The Breakthrough Institute estimates that by 2030, the alternative protein industry can create 200,000 jobs in the US, while also significantly reducing emissions. For countries that already have world-leading expertise in these technologies, there are also questions about how to expand their use around the world, and how agricultural, environmental and development policy will work in unison.

Although private investment in alternative protein startups has soared in recent years, there is still a role for governments to help drive alternative proteins to scale. The Good Food Institute claims that public funding is needed to "spur new knowledge and technical innovation". Table 5 shows how governments have the capability to both encourage and stifle innovation in the alternative-protein sector through investment and regulation.

**Table 5 – Global policies relating to alternative proteins and their impact on innovation**

| Country/ Region | Policy | |
|---|---|---|
| **Singapore** | Singapore has become an innovation hub for alternative proteins. It is investing S$144 million in its Food Story R&D Programme, which includes research for cell-based meat<br><br>Singapore is also taking steps to become the first country to give regulatory approval to cultivated meats | **Positive impact on innovation** |
| **Japan** | In June 2020, Japan announced that its Agriculture, Forestry and Fisheries Ministry would draw up rules for artificially produced foodstuffs using advanced technologies | |
| **Denmark** | Denmark is considering proposals for imposing a red meat tax. | |

| | | |
|---|---|---|
| **France** | In April 2018, the French National Assembly passed an amendment to the country's Rural Code, prohibiting the use of meat terms to describe plant-based foods. | |
| **Mississippi, US** | In 2019 Mississippi introduced a law criminalising terms like "veggie burger" and "vegan hot dog". | **Negative impact on innovation** |

*Source: TBI analysis*

**Key takeaways for policymakers:**

- If more people ate alternative proteins instead of conventionally produced meat, it could deliver huge benefits to the environment and economy. But alternative proteins still only hold a small proportion of the market share.
- Developed-country governments should strongly consider investing to advance alternative protein research and development, as well as policy and advocacy for consumer acceptance.
- Policymakers should work with industry and innovators to take a proactive rather than reactive approach to novel food regulation.

### New Foods and New Farms: Threats/Risks

Food and agriculture innovations offer a major opportunity to change our food system for the better, and any government that fails to support the modern food industry risks falling behind and remaining vulnerable to the impacts of climate change and pandemics. A move towards a technology-driven food system will also create many more jobs. But new technologies could pose a risk of inadvertently threatening traditional agriculture, cultural practices and rural communities in the long-term. Managing this transition responsibly will be a significant political challenge.

**Skills and employment:** The transition to a food system that embraces technologies will create new jobs, but it will also threaten existing jobs in traditional agriculture. In the UK, our current food system provides one in seven people with jobs. In Kenya, the livestock subsector employs 50 per cent of agricultural labour and has the highest employment multiplier. There are around 450 to 500 million smallholder farmers globally. Inevitably, as innovations gain a greater presence in the food system, the nature of employment will change too. A report by the think tank RethinkX has predicted that demand for cow products will have fallen by 70 per cent by 2030, which would bankrupt the US cattle industry. Professor Tim Benton, research director at Chatham House, has previously said the meat industry faced the same risks as the fossil fuel industry. Goldman Sachs has ranked livestock alongside coal as one of the two most precarious commodities.

The threat to jobs appears slightly less significant when considering that today, fewer people work on the land than ever before. In 1900 around 41 per cent of America's labour force worked on a farm; now the proportion is below 2 per cent. And there is a similar (but less marked) picture in less developed countries, as the share of city-dwellers continues to increase. Meanwhile in Britain, Brexit is likely to make it difficult for farms to access labour from Europe, strengthening the case for increased automation and higher-tech farming methods. It's also increasingly likely that traditional farming will become less sustainable as farmers find it harder to make a profit in the face of severe weather, climate change and declining soil fertility.

Innovations like vertical farming and alternative proteins will provide new jobs, but the skillset for the modern farm is likely to be significantly different to today's. For example, vertical farming may create new career opportunities for technologists and project managers and may provide new jobs in engineering, biochemistry and biotechnology. There could also be a major opportunity for many workers in the Western world to retrain in regions where manufacturing and associated jobs are hollowing out.

Some of the innovations set out in this paper will enable countries to have greater self-sufficiency when it comes to food production. However, this could create knock-on effects for other countries. For example, vertical farming is designed to grow food where it is to be eaten. There is no export model, meaning countries with vertical farms may not need to import crops or vegetables from other countries. There's a possibility that this may widen the wealth gap.

**Culture and community:** Farming is central to our rural communities, with family farms making up 90 per cent of the world's farms, including in North America and Europe. For many people, farming is not just a form of employment but a way of life. The fisheries challenge resulting from Brexit has been politically sensitive, yet fishing is only a small part of the economy and will have a relatively low impact. New technologies in the food system could potentially affect millions of people and therefore poses a much greater political challenge.

Policymakers have a duty to encourage this transition responsibly. There are trade-offs that governments should start planning for now.

> **Key takeaways for policymakers:**
>
> - Novel methods for producing foods such as vertical farming and lab-grown foods could pose a risk to traditional agriculture, and the possible impacts should be anticipated by policymakers now.

- As we embrace new technologies, new types of jobs will be created. But the skillset for the modern farm is likely to be significantly different to today's.
- The pace of technological advancement will also require policy solutions to avoid social breakdown. Agricultural-transition funds and retraining schemes are tools policymakers may consider to prevent some workers from losing out.
- Farmers with appropriate land could be offered financial incentives to grow the culture medium used to produce alternative proteins. Some farmers could be paid to rewild land, and farmers heavily reliant on livestock agriculture could be retrained in urban farming. For those who cannot adapt, help in the form of debt-relief programmes should be considered.

### Digital Marketplaces and Mobile Services: Strengths

New digital marketplaces have been developed to address a range of market needs in agriculture, such as global and regional access for suppliers, and greater traceability and price transparency for customers. Covid-19 has also highlighted the need to have a resilient food supply chain. In 2019, 4 per cent of total investment in the agri-foodtech space was invested in agribusiness marketplaces. Startups offer a range of products, such as trading platforms to facilitate sale, leasing and rental of machinery and equipment, business-to-business procurement of food or equipment, and better access to finance and insurance products for farmers.

Mobile technologies and digital marketplaces improve both economic and environmental outcomes, yet delivering on these outcomes requires infrastructure and connectivity, affordability and digital literacy.

- **Economic opportunities:** At scale, digital platforms can reduce the costs associated with buying and selling goods. For example, they can link agricultural businesses to a large market of buyers, often bypassing or at least reducing the disproportionate share of profits taken by intermediaries. They also make it easier for farmers to plan, and increase the likelihood of a reliable income, meaning farmers can invest in other productive activities. These platforms are particularly beneficial in the developing world; a study in Zambia showed that hiring tractor services leads to higher farm profits. As Africa's population is expected to grow and the demand for food and jobs increases, these platforms are likely to play an increasing role.
- **Environment opportunities:** By increasing efficiency and optimising resource use, the uptake of digital and mobile services has positive environmental impacts. For example, there is the potential to reduce price dispersions across markets, reduce oversupply and lower food loss and waste.

**Key takeaways for policymakers:**

- Digital marketplaces can significantly improve social and economic outcomes for farmers, as well as help to reduce waste, especially in the developing world and emerging economies.

- Encouraging the development and adoption of digital tools and mobile services is likely to require investment to improve basic digital infrastructure, literacy and affordability.

### Recognising Limitations

Although food technologies offer many opportunities, they are not a panacea. We must not use food technologies to detract from other important issues in our food system that require different solutions.

One critique of some new food technologies is that while they often help increase the efficiency of production, the lack of access to food is actually due to uneven distribution, and therefore simply producing more food will not allow us to improve food security for marginalised groups.

It has also been argued that a focus on high-tech solutions may lock us into or reinforce sub-optimal production methods. For example, although precision farming can enable more precise application of agro-chemicals, it merely results in making an intrinsically damaging approach less harmful. For this reason, it is important to take a broad look at the food system as a whole, and work out which innovations are most effective in which circumstances. Some technologies may only be appropriate once the basic building blocks of efficient crop production are in place, particularly in developing countries.

Although food technologies can make a meaningful impact, they often won't offer perfect solutions. The key task for policymakers, innovators, scientists and investors is to come together to work out how to deploy and scale food technologies in the right way to have the greatest positive impact.

# Getting From Opportunity to Reality Requires Progressive Actions

Applying technology for the greater good is one of the most important challenges of our time. The benefits of adopting a technology-first strategy for the food system are clear. Yet, many food technologies are untested at scale. How we develop and deploy these technologies is key.

In the last decade, through a mixture of funding early-stage energy science and tech R&D, and a breadth of state and national subsidies and incentives, clean-energy technologies have become increasingly attractive to the entire world.

We now need a similar transition in our food system. With the right technology stack, we have the potential to transform the industry from top to bottom, improving choice and creating wider multiplier effects and increased standards of living for people all over the world.

This section considers each innovation's chances of scaling. It looks at the certainty of scaling to benefit the global population, the likely time-horizon and the main barriers to implementation.

### Measuring the Impact and Certainty of Innovations

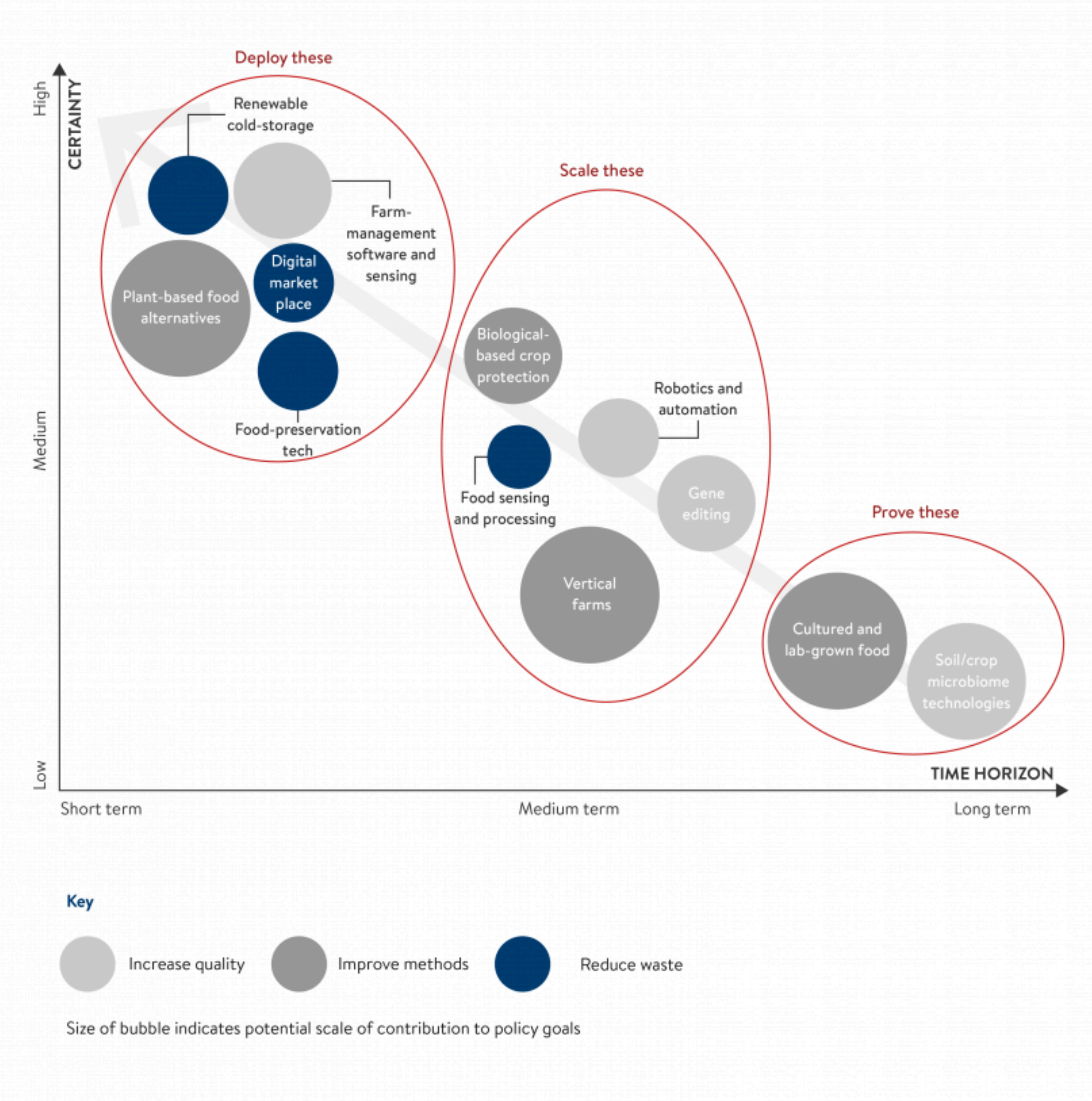
Although food and agriculture innovations offer significant opportunities, there is no guarantee that they will be scaled up at sufficient pace to deliver on their full potential.

Typically, large-scale transformations of sectors are slow. To date, innovation in the food and agtech sector has typically been incremental rather than transformational. In 2018, food production ranked last in terms of adopting digital technologies; digital penetration was 0.3 per cent compared to 12 per cent in retail. And even though it is catching up, many innovations are still not yet available on a large scale.

Figure 3 assesses the relative certainty and likely time-horizon for each innovation to be developed, commercialised and scaled.

It also evaluates the relative contribution of each innovation to achieve the three policy goals when scaled. It distinguishes those technologies with high certainty, which could be deployed now, and those which are longer-term and less certain, and therefore may warrant higher-risk investment and R&D.

**Figure 3 – Measuring the impact* and certainty of innovations**




*Source: TBI Team analysis. * Impact refers to the contribution of the technology to policy goals if scaled up (environment, economy and health). This is based on a qualitative assessment. More details are provided in the annex.*

Policymakers should pay attention to the promising technologies and innovations that could have an impact today, as well as those that could transform our food system in the future.

## Removing Barriers and Accelerating Progress

Without action – most likely from a whole range of actors – there is a significant risk that many transformative technologies won't be implemented responsibly at sufficient scale or pace. To make these technologies work for everyone, everywhere, we need a better understanding of the challenges, how to overcome them and who is responsible.

Technologies can be categorised depending on their stage of development: There are those that can be deployed, those that should be scaled and those that must be proved (or are still in discovery or development). The factors that are preventing progress for each of these groups generally differ. Although there are many factors that may be holding back progress, here we set out some of the main challenges.

Harnessing the opportunities presented by these innovations will be partly in the hands of policymakers. But it's also likely that several actors across multiple countries will need to come together to overcome these challenges, including (but not limited to) farmers, producers, retailers, tech companies, investors, entrepreneurs, academics and scientists.

**Deployment**

The first task for policymakers is to work out how to successfully deploy the high-certainty, short-term innovations, such as plant-based meat and precision-agriculture technologies. Progress in these technologies is generally held back by vested interests and a lack of demand.

**Vested Interests**

Some actors in the food system may have a vested interest in maintaining the status quo. This in turn can prevent progressive policy in relation to food and agriculture technology. For example:

- There could be tensions between new farming initiatives and farmers using older methods, who may consider those promoting new farming initiatives a threat.
- Misplaced incentives in large parts of the world contribute to environmental damage in food systems. EAT-Lancet published a report that cites "decades of policy failure" to blame for slow progress in food systems. It notes that policy responses to the joint challenges of obesity, undernutrition and climate change have been unacceptably slow due to reluctance of policymakers to implement effective policies and opposition by vested commercial interests.
- A report from the Food and Land Use Coalition shows that just 1 per cent of the $700 billion a year given to farmers is used to benefit the environment. Instead, much of the total promotes high-emissions cattle production, forest destruction and pollution from the overuse of fertiliser.
- The US government spends up to $38 billion each year subsidising the meat and dairy industries, which creates an uneven playing field for plant-based alternatives.
- There could be tensions and sometimes trade-related restrictions between existing national regulatory authorities and systems that are designed for current farming methods.

**Demand**

For food technologies to be deployed, there will need to be adequate demand from consumers, producers and farmers. Consumer acceptance of a technology can depend on a number of factors, such as the perceived ease of use of the technology, the perceived usefulness, and attitude towards use. Take-up on a large scale will require technologies to be more affordable, practical and efficient than incumbent techniques or products. However:

- Some consumers are critical or sceptical of new technologies in food. For example, perceptions around plant-based and cultured meat are varied, although these alternative proteins are gaining increasing acceptance. There are also companies exploring opportunities to create foods that suit certain consumer taste palettes. For example, Singapore-based company AI Palette is using artificial intelligence to help food companies better understand consumer trends and validate product concepts.
- Outcomes from the UK's net-zero Climate Assembly showed people expressed strong concerns about food grown in labs.
- Plant-based meat has not yet reached cost parity with conventional meat, and despite a growing interest in sustainable eating in some parts of the world from conscious consumers, these people only make up a minority. The challenge for alternative proteins and lab-grown foods will be to create a product which is competitive in price, convenience and taste. Tesla hasn't become successful because of consumer demand for sustainability, but because it created a better product. The food and agriculture industry must to do the same by appealing to its end users – whether that's farmers, consumers or retailers.
- Ethical concerns and perceived risks around certain technologies also play a negative role. Some consumers view foods produced with technologies as having higher risk when compared to organic or "natural" food. Consumers may also reject new technologies due to perceptions on food safety.
- The adoption of technologies by farmers (such as robotics and automation) is often constrained by their ability to pay for the technology and their ability to easily operate the technology. In some cases there is a lack of farmer trust and acceptance.

**Scale**

Medium-term, medium-certainty innovations should be responsibly scaled. This is currently mostly being prevented by a lack of risk capital, and infrastructure and inputs such as energy.

**Lack of Risk Capital**

Investments in food and agriculture technologies have the potential for an extremely high return for society as a whole: They can solve both sustainability and health challenges and create new economic opportunities. However, investments in some of the early-stage technologies required to scale up innovations are also high risk. This has meant that, although investments have increased over time, there has generally been a limited appetite to fund some of these technologies. For example:

- Research from WEF shows that there has been $14 billion in investments in 1,000 food systems-focused startups since 2010, whereas health care attracted $145 billion in investment in 18,000 startups during the same period.
- Many food-systems technology innovations fail to reach any meaningful scale.

It's likely that government intervention will be required to fund academic and basic R&D of innovations that are not yet ready to bring to market, and some of the patient long-term capital needed for food technologies to succeed. Doing this successfully will require much better shared knowledge of which innovations work best in which contexts.

**Infrastructure and Inputs**

Scaling up food technologies requires infrastructure and inputs such as energy. In some cases, this is seen as a barrier to scaling them up. For example:

- Most of the technologies set out in this report require internet access to work effectively. Sometimes a lack of internet connectivity can act as a barrier to farmers adopting technologies. For example, internet connectivity issues in developing countries can mean that wireless precision-farming tools like sensors don't operate properly.
- The high energy requirements of vertical farming are expensive and mean that it is currently confined to high-value crops. If renewable energy sources are not used to meet this need, vertical farming could have a high environmental footprint.
- Currently, it is not cost-effective or a good use of land to install enough solar panels to run an entire farm, but if efficiencies come into play, this could change in the future.
- Some innovations – like vertical farms and insect farms – will require massive capital for infrastructure, which will likely need government intervention to deliver.

**Proof**

Low-certainty, longer-term innovations need to be properly proved before they can be scaled and deployed. These innovations are most commonly held back by regulatory burdens and a lack of basic science and R&D.

**Regulatory Burdens**

Well-thought-through regulation is key to innovation in food systems. The right regulations are also key to ensuring that food and agricultural technologies are deployed responsibly and are constantly improving. However, outdated, lengthy or overly complicated regulation could prevent innovation (in some cases, it already is). For example:

- Regulation that is uncertain or difficult to navigate can reduce startup success.
- The US Food & Drug Administration has previously been criticised for not providing more guidelines for food technology companies on what is acceptable and what is not.
- New legislation has been passed in some jurisdictions that prevents companies using the term "meat" for anything other than conventionally raised meat. This could prevent innovation in the alternative-protein market.
- Different regulatory frameworks in different countries could present a barrier to cooperation to advance innovations and a barrier to global trade.

**Basic Science and R&D**

Making these innovations work at scale demands a very large stack of technologies. Some of the technologies and breakthroughs in science required to make these innovations work commercially at scale are currently not available or are still in development. For example:

- Despite the concept being proved, cultured meat is not yet commercially available, and must overcome significant technical challenges before it can hope to become price competitive with conventional animal products. Some of the technical challenges relate to how to source the cells to form the tissue. Other challenges include developing the tissue scaffolds needed to support the growth of the cells, and to engineer the specialised bioreactors needed to scale up production.
- Other lab-grown and synthetic foods could be available in the future but haven't yet been proved in the lab.
- There has been significant underinvestment in research and technology development for crops and livestock that are important to farmers in low-income contexts.
- The interactions between human and environmental microbiomes is an emerging area of research, but one that has the potential to revolutionise agriculture.

There's a strong case for government to fund academia and basic R&D of innovations that are not yet ready to bring to market. ARPA-E in the US has played a positive role in identifying revolutionary advances in applied sciences and translating them into technological innovations.

# Conclusion: Policy Questions to Address

New and emerging food and agriculture technologies offer the opportunity to make the world a significantly better place, and a radically different vision for our food system is now much closer to becoming a reality. However, despite the promise of these innovations, there are several challenges that must be addressed for them to scale up responsibly. Our future food system therefore demands a new set of answers to a new set of questions.

## What Will It Take to Make These Technologies Work for Everyone, Everywhere?

1. **How do we make the unit economics of food technologies work globally – not just in California or the UAE?**

Potentially revolutionary innovations like vertical farming are not yet economically feasible on a large scale. Furthermore, most vertical farms that currently exist are in high-income countries. But challenges in our food system are global, and we need global solutions. If we are going to make these technologies work for everyone, we need to work out what it will take to make the unit economics work everywhere. It's likely that existing technologies and components will need to fall in price and new technologies will need to be developed.

It's also likely that new funding models will need to be considered. It's possible that the venture-capital model won't be sufficient to fund vertical farming on a large scale. To create a vertical farm which can produce enough food to feed large populations will require substantial capital expenditure. It raises an infrastructure question as much as a funding question, and governments are likely to need to play a major role.

Additionally, millions of people around the world currently grow, fish or hunt food to feed their own families. It's far from clear how these people will get the cash to buy food produced in labs or on vertical farms.

2. **What is the role for government vs. the private sector to drive food tech to scale?**

It's likely that market forces will enable some technologies to thrive, while others will require government intervention to have a positive impact on the world. For example, investment in alternative proteins has grown massively in the past decade. But the sector still only holds a small market share compared to the traditional meat industry. As a result, the Good Food Institute has argued for public funding to advance alternative protein research. Governments already spend around half a trillion dollars every year supporting agriculture and the food system, yet this investment is not producing desirable outcomes.

Our initial analysis suggests that scaling up food technologies necessitates far more government intervention than already exists. Governments need to work out where intervention may be necessary to encourage innovation, and how to create an enabling environment or "innovation ecosystem" so the private sector can thrive.

The right regulatory system will also be key, as will a strong relationship between the public and private sectors.

3. **How can we help farmers adopt these technologies, and make technologies more attractive to consumers?**

Many of these technologies require both capital investment and training to use them effectively. This means that, when combined with cultural inertia and sometimes low trust and awareness in technology from farmers, uptake of technologies that already exist can be low. For example, the uptake of precision-farming technologies globally is still fairly low. Governments must consider the kinds of interventions required to encourage farmers to use effective technologies that already exist. This may include better information and demonstration of the value of technologies, alongside financial support.

Similarly, there remains some consumer scepticism around many technologies like novel foods. Aside from making these products competitive in convenience, price and taste, there may be other interventions we can make to make them more attractive to consumers, like increasing education and dialogue around these technologies, therefore building trust and acceptance.

4. **How might employment be affected? How can we make sure we create more winners than losers?**

Farming is a sector that largely takes place in rural communities. The agricultural sector employs more than 25 per cent of the world's working population. In the developing world four-fifths of food is produced by smallholder farmers. Innovations such as precision farming, alternative proteins and vertical farming are likely to change the nature of food production and therefore change the nature of work. For example, to compete with industrial agriculture, vertical farming will need to be better at reducing the need for human labour, which essentially means technology will have to replace human jobs. We need to work out how to make this transition as smooth as possible so people do not lose out.

There's also a possibility that some innovations open up the wealth gap. Vertical farming, for example, has no export model, meaning countries with vertical farms may no longer import crops or vegetables from other countries.

The agricultural revolution will also create new jobs and will necessitate new types of skills. Supporting the development of new skills will be a central task for governments wanting to support the food-technology revolution.

5. **Which technologies should be prioritised? Can and should multiple technologies work**

**simultaneously, or will some compete with others?**

We need to ask ourselves what we want our future food system to look like. Is it desirable to grow most of our food in cities in vertical farms, where it is to be eaten, or should traditional farms – made more efficient with precision farming – still dominate? Will these approaches compete in our future food system? And therefore, which ones should governments support? Do we want all our meat to be grown in labs in the future, and therefore is there any role for technologies that improve the efficiency of livestock farming? Henry Dimbleby writes in Part 1 of England's National Food Strategy: "It seems to me that our only real hope of creating a sustainable food system lies in diversity … if one part of the system gets struck by disaster, the others can pick up the slack." Indeed, the answer may well be that an ideal future food system includes a mixture of different innovations and methods. It's also likely that many innovations will complement each other to create an even greater positive impact than they could alone. Our analysis suggests that vertical farms and alternative proteins have the potential to be some of the most transformative innovations.

These questions provide a starting point for any government that wants to grasp the opportunities presented by innovations in the food industry.

Given the impact of our current food system on our health, the environment and our economies, and the positive potential of these food technologies to address each of these factors, embracing new innovations in our food system could be the single-most effective thing we can do to build a better future. This paper should provide hope that this future is not beyond our reach.

Technology is already transforming every aspect of the world we live in; like every other part of our economies and societies, technology will change the way we produce and consume food. But it's up to governments to set the direction and pace of this change. Governments should strive to get ahead and start to build the markets of the future.

We will explore some of the issues and questions laid out in this paper over the coming months, to better understand how to responsibly scale up transformative food technologies, and create a food system that works for everyone, everywhere.

# Appendices

## Appendix 1: Increase Quality

| Category | Opportunities and challenges: Environment | Opportunities and challenges: Health | Opportunities and challenges: Economy | Other challenges | Threats |
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| **Precision:** Robotics and automation | - More precise and accurate farming methods can lead to reduced loss and more accurate application of inputs such as water and fertilisers<br><br>- Supports sustainable intensification<br><br>- Lighter farm machinery and drones will help reduce soil compaction. | - Could increase productivity and therefore food security<br><br>- Using fewer agrichemicals is good for the soil and therefore the nutritional. value of crops (maximises crop uptake of nutrients)<br><br>- One of the most common sources of injury and death on a farm is the mechanical | - Soil degradation costs farmers in the UK alone around £246 million per year, mainly through lower yields and higher fertiliser costs. Precision farming methods could dramatically decrease this, but would likely be over the longer-term<br><br>- Increased productivity and reduced labour costs means farmers | - Steep learning curve for farmers who adopt precision technologies<br><br>- Lack of farmer trust and acceptance<br><br>- Requires interoperability between robots and existing machinery. There is currently a lack of compatibility between software produced by different manufacturers.<br><br>- Technologies are still expensive | -May remove farmers from their farms, leading to a loss of know-how<br><br>-Farms may not require human labour<br><br>-If robots don't have proper built in safety features, they could be dangerous<br><br>-Increasing use of robotics, automation and precision |

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| | Robots allow re-aeration of the soil when they replace traditional heavy tractors<br><br>- Crop weeding robots can reduce the need for herbicides<br><br>- Can better monitor and improve livestock health | linkages in large farm machinery. Automation of farm equipment could increase safety<br><br>- Fewer emissions from farm machinery means less pollution | can make bigger profits<br><br>- The average age of a UK farmer is 58 years, in Japan it is around 70 years - automation can help with a declining workforce<br><br>- There are also cost savings at a societal level | | agriculture threatens the loss of over 20 million livelihoods in East Africa<br><br>-Reduces rather than eliminates pesticide use – risk of technological lock-in<br><br>-Could reinforce existing inequalities as many smallholder farmers in the developing world cannot access or work with data |
| **Precision:** Farm-management software and sensing | - Farm-management software means farmers can make much better | - Precision agriculture means farmers can use fewer harmful chemicals. | - Sensors linked to smart applications will be able to send alerts and reduce daily routine jobs – | - There is currently a lack of compatibility between software produced by different manufacturers. | - Loss or misuse of data could result in financial or environmental losses |

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| decisions about farming methods. E.g. how to apply the most efficient amount of fertiliser and water<br>- Fewer carbon emissions emitted (fertilisers result in the production of nitrous oxide – a greenhouse gas)<br>- This means that soils, groundwater and the entire crop cycle benefits | - Soil depletion as a result of over-use of agricultural chemicals affects the nutrients or our foods, and in turn, our health. Precision agriculture enables us to use fertilisers more sparingly so can improve soil health.<br>- More productive use of land can lead to less ecological degradation and a reduced threat of zoonotic diseases.<br>- More efficient farming means increased food security. | reducing labour costs<br>- A report shows costs savings ranging from $13 to more than $25 per acre when growers use GPS yield or soil maps in conjunction with auto-steer and variable rate technology when applying inputs<br>- Farmers can reduce costs by saving on water, pesticide and fertilisers<br>- Increases productivity, makes farming more efficient and therefore more profitable<br>- National geographic found that when farmers in the US started | - High sensor costs<br>- Technologies come with a steep learning curve<br>- Questions remain around data-ownership<br>- |

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| | | | implementing precision ag technologies, their gross annual benefit went up. Small farms earned $11,00 more and large farms $39,000 more<br><br>- According to the International food policy research institute, using precision farming techniques and new technologies could help to increase crop yields by up to 67%.<br><br>- There are also costs savings at a societal level | | |
| **Protection:** Gene editing | - Opportunity to improve yield and increase | - Produce could be designed to have greater | - Economic opportunity for farmers as crop yield/ | - Public acceptance could be low, as with GMOs | - Risk of the science outpacing |

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| | resilience to climate stresses. This means less ground is needed to produce crops<br><br>- Opportunity to advance the plant architecture for vertical farming through gene editing, making vertical farming more feasible | functional benefits, such as higher vitamin and mineral content<br><br>- Can design heathy produce to be more convenient for the consumer and therefore more attractive to buy. E.g. seedless watermelon or baby-cut carrots<br><br>- CRISPR could be used to improve health of animals reduce the use of harmful antibiotics | productivity is increased<br><br>- Gene editing is cheaper, simpler and faster than creating GMOs | - Regulation could hinder progress. E.g. European Court of Justice ruled that organisms obtained by gene editing techniques are subject to the same regulations as GMOs | public consent<br><br>- Raises ethical issues: how far should we take CRISPR?<br><br>- Could be used for other damaging activities. E.g. making designer babies<br><br>- A potentially unpredictable impact on human health<br><br>- Unequal access to technologies like gene editing could increase inequality |
| **Protection:** Soil health / | - Technologies that enable us to explore the | - Increase productivity | - Technological advances in microbiome | -There is a wealth of unexplored knowledge about | - Potential ethical concerns if |

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| microbiome technologies | role of microbes and composition of microbiomes in agricultural systems, and that allow the manipulation of crop microbiome can help us optimise ag systems to enrich, rather than deplete the soil. For example, further research could reveal opportunities for microbiome engineering<br><br>- New technologies could allow the exploitation of insect microbial symbiosis to control agricultural | and ensure food security<br><br>- Ensure nutrient security and healthy food<br><br>-Microbiome technologies could reduce the use of chemical pesticides, resulting in positive health implications | science will likely help farmers around the world grow more food at a lower cost, through reduced fertiliser use and water use<br><br>- Boosting plant resilience to stress could reduce waste.<br><br>-Microbiome tools can substantially increase economic performance by commercialising new products | the role of soil microbes in ecosystem functioning. We are only just starting to understand the organisation of these complex communities, and the interdependencies among themselves and with the biotic (plant) and abiotic (edaphic) environment.<br><br>- We need technological advancements to realise the potential of microbiomes<br><br>-For example using multidisciplinary approaches to integrate emerging technologies (omics, 3D printing, synthetic biology) with more traditional | the soil/crop microbiome is manipulated |

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| | pests and protect pollinators<br><br>-Microbiome research may provide solutions on how humans and other life forms on earth can withstand climate change | | | approaches of microbial ecology<br><br>- Public acceptance will be crucial for the success of these technologies<br><br>- Understanding the relevance of the microbiome to agriculture is a top research priority.<br><br>-For example, identifying the metabolic pathways of the microbiome will help in designing tools to manipulate the phytomicrobiome to sustainably increase productivity | |
| **Protection:** Biological-based crop protection | - Products enable pest-management without the use of harmful agri-chemicals | - Products can trigger enhanced nutrient use in crops and enhance the availability of | - Biologicals help improve crop yields, and provide ways of controlling pests and diseases | - Deliver lower levels of control and more variable performance than their chemical counterparts. | - Body of evidence on efficacy and safety of biologicals such as biofertilisers, |

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| | - Increased yield means reducing land use to produce food | nutrients in the soil | - Globally, farmers lose 30-40% of their crops because of pests and diseases. Biologicals can help to reduce this. | - Crop pests and pathogens come in all shapes and sizes, and from multiple kingdoms of life. This poses an enormous challenge for the development of biocontrol approaches that are highly-target and adaptable for a range of different organisms<br><br>- There is currently fairly low uptake from farmers. Farmers want to know that these products actually work effectively | biopesticides or biostimulants, needs to grow |

## Appendix 2: Improve Methods

| Category | Opportunities and challenges: Environment | Opportunities and challenges: Health | Opportunities and challenges: Economy | Other challenges | Threats |
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| **New foods**: plant-based alternatives | - Given the negative impact of meat production on the environment, and the fact that meat consumption is likely to grow as nations develop, plant-based and cultured meat could significantly reduce GHG emissions from the production of livestock and feed.<br>- It could also deliver reduced water use, and land use. E.g. it's claimed that the Impossible burger has 89% fewer emissions, uses 96% less land use and has 87% less water footprint than its beef alternative | - Less prone to biological risk and disease compared to animal protein. For example, there is no risk of salmonella or e coli<br><br>- Antibiotics is not used in the production of alternative proteins, so there is a decreased threat of anti-biotic resistance<br><br>- The significantly lower environmental impact means there is likely to be a lower risk posed by zoonotic diseases | - The Breakthrough Institute estimates that by 2030, the alternative protein industry can create 200,000 jobs in the US<br><br>- Huge economic opportunities through reduced environmental impact | - Consumer acceptance – many consumers still think actual meat is the best source of protein | - Could reduce the size of land-based sectors and have a negative impact on the social and economic fabric of rural areas.<br><br>- It could affect the economies of countries dependent on livestock |

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| | | - Plant-based foods can be better for human health – they have no cholesterol or trans fat | | | |
| **New foods**: lab-grown and synthetic foods | - As the population grows, meat production is expected to grow by 70%.<br><br>- It is scientifically impossible to meet global goals for cutting greenhouse gas emissions without addressing the climate impacts of factory farming<br><br>- Given the negative impact of meat production on the environment, and the fact that meat consumption is likely to grow as nations develop, plant-based and cultured meat | - Less prone to biological risk and disease compared to animal protein. For example, there is no risk of salmonella or e coli<br><br>- Antibiotics is not used in the production of alternative proteins, so there is a decreased threat of anti-biotic resistance<br><br>- The significantly | - Possibility to produce cheaper foods (research from Rethink-X suggests proteins from precision fermentation will be around 10x cheaper than they are today<br><br>- Huge economic opportunities through reduced environmental impact | - The growth medium for lab-grown meat is expensive<br><br>- Other technical challenges include cell source, mimicking the in-vivo myogenesis environment, and bioprocessing for commercial-scale production<br><br>- Low consumer acceptance and worries about | - Potential concentration of farmfree foods through patenting of key technologies<br><br>- Many synthetic foods require feedstocks for the fermentation process. This raises concerns about where the feedstocks will be used, and how sustainable it is.<br><br>- Production can be very |

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| | could significantly reduce GHG emissions from the production of livestock and feed. - It could also deliver reduced water use, and land use. | lower environmental impact means there is likely to be a lower risk posed by zoonotic diseases<br><br>- Potential to create much healthier foods. For example tailor-made nutrition | | products not being natural | energy intensive. If this energy is not from sustainable sources, it could make climate change worse.<br><br>- It could affect the economies of countries dependent on livestock |
| **New farms**: Controlled environment agriculture and vertical farms | - Research has shown that  wheat grown on a single hectare of land in a 10-layer indoor vertical facility could produce…220 to 600 times the current world average wheat yield of 3.2 t/ha. This could be achieved whilst reusing most water, minimal pesticides and | - Potential for increased food security in the face of climate change and diminishing land and water resources<br><br>- Reduced occurrence of pathogens<br><br>- Produce food not contaminated | - Eliminate transportation costs<br><br>- Genetics research has a possible role to play in matching plants to the available light spectrum for improved yield.<br><br>- No requirements for fertilisers, | - Costs of building a vertical farm are currently extremely high.<br><br>- Limited range of crops suitable for the business model<br><br>- Start-up costs are high, especially if land is | - Microbial impacts on plant health and production is relatively unexplored in controlled environments. I.e. we don't know enough about the contribution of soil to nutrition, and therefore the true effect of soilless |

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| herbicides and no nutrient losses<br><br>- All year round production can be controlled on a demand basis, minimising waste<br><br>- Reduction in use of fossil fuels (no tractors, machinery or shipping)<br><br>- Potential for provision of energy to the grid through methane generation<br><br>- Potential to rejuvenate the natural ecosystem so that rural land is reclaimed for vegetation<br><br>- According to the FAO, vertical farming consumes 75% less raw material than traditional farming and just 60 watts of power daily to grow 150kg of | from chemicals<br><br>- Reduced distance travelled means food is fresher and therefore healthier | herbicides or pesticides<br><br>- No need for farm machinery such as tractors, trucks or harvesters<br><br>- Provide new jobs in engineering, biochemistry, biotechnology, construction, maintenance, and research and development opportunities for improving the technology<br><br>- Greater productivity could lower food costs<br><br>- Reduced losses and all-year-round production | purchased in central business districts<br><br>- Need to train a skilled workforce | farming on our health<br><br>- The need to manage disruption to the rural sector<br><br>- There is no export model for vertical farming, which has real implications for widening the wealth gap |

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| | vegetables in a month<br><br>- Local production and eliminates food miles<br><br>- Could hand vast areas of land back to nature<br><br>- Significantly decreased deforestation | | | | |

## Appendix 3: Reduce Waste

| Category | Opportunities and challenges: Environment | Opportunities and challenges: Health | Opportunities and challenges: Economy | Other challenges | Threats |
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| **Supply chain**: food sensing and processing tech | - Advancement of nanotechnology has provided opportunities for the development of new sensing and food | - Approximately 48 million people are affected by diseases caused by bacteria, viruses and | - Food scandals have been caused by the use of illegal or unsuitable ingredients. E.g. the horsemeat scandal in 2013 wiped over £300 million | - Getting producers to adopt these technologies when they don't necessarily understand the insights | - If algorithms are not accurate and precise, food could be unnecessarily lost or wasted. |

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| | packaging solutions<br><br>- Can extend shelf-life and reduce waste. E.g. food freshness sensors can reduce the need for sell-by dates | parasites per year<br><br>- Sensing technologies can assess safety and quality of food (e.g. freshness, detect allergens, toxins or pathogenic contaminants) | off the value of a UK retailer and could have been avoided if identified earlier in the food chain. Hyperspectral imaging could enable food processers to continuously monitor components of food along the production line, reducing losses/ Combined with an IoT system it could provide instant alerts.<br><br>- Food fraud costs the global economy an extra $40 billion per year. Scandals have increased by two-thirds since 2010 | - Technical challenges remain, particularly with hyperspectral imaging<br><br>- Detecting small foreign objects requires further technical improvements, but would also increase cost |
| **Supply chain**: Food | - Can help to keep food fresh, without | - Less food wasted means | - Economic gain for producers as a | |

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| preservation tech | the need for chemicals<br>- Reduces waste<br>- Biodegradable packaging reduces the use of plastic | increased food security | result of reduced waste | |
| **Supply chain:** Renewable cold storage | - Off-grid cold storage helps farmers reduce post-harvest losses, even in remote areas who are not yet connected to road and electricity<br>- Food waste is the third-largest emitter of $CO_2$ globally<br>- Moving from diesel-powered generators for cold storage to renewable cold storage units reduces emissions | - Reduced emissions means lower pollution levels<br>- Can help increase food security as less food is wasted | - Smallholder farmer incomes are reduced by at least 15 per cent because of post-harvest losses<br>- As prices usually fall during harvest time, off-grid cold storage allows farmers to cut waste and get better prices which leads to higher productivity and income | - High initial cost/ investment. |

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| **Marketplaces:** agri-food marketplaces and e-services | - Potential to reduce price dispersions across markets, reduce oversupply and lowering food loss and waste<br><br>- Improve access to finance and better ways assessing weather, market, and credit risk | - Could increase quality of life for farmers<br><br>- Addresses distribution challenges and can increase food security in vulnerable areas | - Can improve small-holder farmers' access to mechanisation services and reduce unit costs and increase competitiveness<br><br>- A study in Zambia showed that hiring tractor services leads to higher farm profit<br><br>- Increased access to information about market prices via mobile phone can increase farmers' bargaining power and increase sales<br><br>- Numerous studies have shown that digital financial solutions have a positive impact on annual | - Internet penetration rates vary in the developing world. Telephony penetration rates were 44% in Sub-Saharan Africa in 2018 compared with a global average of 66%. | - Could increase the digital divide and potential benefits could be unevenly distributed |

household
income

## Appendix 4: Measuring the Impact* and Certainty of Innovations

** Impact refers to the contribution of the technology to policy goals if scaled up (environment, economy and health).*

| **Tech** | *Value (1-5)*<br><br>**Where a score of 5 represents a big contribution to policy goals and a score of 1 represents a relatively small contribution to policy goals* | **Certainty** | **Time Horizon** |
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| Robotics and automation<br><br>(Increase quality) | **2**<br><br>- Precision farming and the use of robotics largely means improving current farming methods rather than radically changing methods.<br><br>- Doesn't reduce the amount of land, or deforestation required to feed populations<br><br>- Doesn't eliminate the need for agrichemicals<br><br>- However, the use of robotics and automation can | **Medium**<br><br>- Market intelligence suggests that the global market revenue for agricultural robotics alone will grow from $3bn in 2015 to $73.9bn in 2024.<br><br>- There is huge untapped potential for UAVs or drones<br><br>- The cost of technologies and ability of farmers to operate remain significant barriers to uptake | **Medium term**<br><br>- Today, drone imagery is used on two out of every ten acres in the U.S<br><br>-Goldman Sachs predicts that the agricultural sector will be the second largest user of drones in the world in the next five years.<br><br>- So far precision farming has largely |

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| | reduce (generally not eliminate) the over-use of agrichemicals. It can increase productivity gains for farmers and leads to economic gains<br><br>- It can also help to restore the soil and increase its ability to store carbon<br><br>- It could also have a positive impact on human health as crops can take on increased nutrients | | been developed in the US. There are still no concrete plans from MEPs to make it a reality in Europe. |
| Precision agriculture and farm-management software<br><br>(Increase quality) | **3**<br><br>-Collecting data offers significant opportunities for understanding correlations in nutrients, water, soil types, and helping to improve farming methods to be better for the environment, and therefore human health<br><br>- Has a wide range of uses, including forecasting and measuring profits, developing crop plans, crop management, labour management<br><br>- However, precision farming largely means improving current farming methods | **High**<br><br>- Farm management software can often be much cheaper than adopting robotics, meaning it is more likely that farmers will adopt this software<br><br>- Many farms already use some type of farm-management software, especially in the US<br><br>-Technology is expected to become increasingly accessible | **Short term**<br><br>- A large number of farm-management software platforms are on the market<br><br>- The global farm management software is expected CAGR of 16.2% from 2017 to 2025 |

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| | rather than radically changing methods.<br><br>- Doesn't reduce the amount of land, or deforestation required to feed populations<br><br>- Doesn't eliminate the need for agrichemicals | | |
| Gene editing<br><br>(Increase quality) | **4**<br><br>- Could have enormous implications for food systems: disease resistance, stress tolerance, improved feed conversion rates, better nutritional content and increased choice for consumers<br><br>- Will have an increased impact as climate change continues to threaten food security, as it can help to make foods more resistant and resilient<br><br>- Could also be used to increase feasibility of vertical farming (by improving crops so they are more successful in vertical farming environments) | **Medium**<br><br>- There are some uses already<br><br>- The progress made since CRISPR was developed is significant<br><br>- There are barriers to overcome before it can be applied to multiple foods, including consumer acceptance and regulatory burdens | **Medium term**<br><br>- The first gene edited crop went on the market in 2018<br><br>- NFU report predicts that biotechnology in food production will be ubiquitous in 20 years<br><br>- There is wide-spread ongoing research<br><br>- CRISPR is relatively easy for those with proper training and basic lab facilities, so is likely to become more feasible in developing countries |

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| | | | - The research, development and regulatory review time is decreased with gene editing |
| Soil health / microbiome technologies<br><br>(Increase quality) | **4**<br><br>- Soil health is under severe threat. Harnessing the soil and plant microbiome and unravelling their complexity offers huge potential for innovation and could help to significantly reduce environmental impact of farming, improve health and increase resilience to climate threats<br><br>- We are now able to explore the role of microbiomes in agricultural systems in far greater depth and resolution than has been possible before. -This could be a major game changer in the way we manage the planet's resources to obtain our food and improve health | **Low**<br><br>- There is so much we still don't know about the plant and soil microbiome. It's estimated that most of the microbial diversity still remains to be explored. This has the potential to correspond to innovative biotechnological developments in the field of agriculture<br><br>- Today's tools can tell us a lot about the molecules in microbial communities, but they cannot explain the function of these molecules and how they enable microorganisms to work together. Only with that level or understanding will we truly be able to harness microbiomes to improve food production | **Long term**<br><br>-Some applications already exist. E.g. but harnessing the soil and plant microbiome is an emerging area of research<br><br>- There is lots of research going on in understanding the plant microbiome<br><br>- A lot remains to be explored about the complex relationship between plant and microbiome<br><br>-Scientists have suggested that given the complexities of the soil microbiota and the variety of signal molecules they utilise, revolutionising agricultural productivity with microbiome |

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| | | | technology is a mid-to long-term goal<br><br>-We need incremental advances as well as quantum leaps |
| Biological-based crop protection<br><br>(Increase quality) | **3**<br><br>- Can significantly reduce the need for harmful agrichemical, increase resilience to stresses and increase yield<br><br>- But currently, these products aren't always effective<br><br>- They also currently only serve to complement, rather than replace chemical products | **Medium**<br><br>- Biological crop protection has seen a dramatic rise in popularity in recent years | **Medium term**<br><br>- The markets for biological control agents and biostimulants are growing at over 10% a year |
| Plant-based food alternatives | **5**<br><br>- Could have a huge impact across all policy goals if scaled up<br><br>- Increased food security and self-sufficiency, even as climate change threatens traditional production | **High**<br><br>- Multiple plant-based foods are already on the market and consumers are increasingly interested. E.g. 28% of consumers are eating more protein from plant sources. | **Short term**<br><br>- Mission of Impossible Foods is to completely replace the need for animals by 2035<br><br>- Research forecasts that the value of the |

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| | - Radical opportunity to free-up land and reduce deforestation, half of the world's habitable land is currently used for agriculture<br><br>- Opportunity to produce healthier food | - Mintel found that 46% of Americans believe plant-based meat is better for you than real meat | global plant-based food and drink market could soar by more than 1000% over the next 10 years, to reach $140bn by 2029<br><br>- UBS predicts the plant-based protein industry can expect a CAGR of 28% by 2030 (from USD 4.6bn in 2018 to USD 85bn). |
| Lab-grown and synthetic food | **5**<br><br>- Could have a huge impact across all policy goals if scaled up<br><br>- Increased food security and self-sufficiency, even as climate change threatens traditional production<br><br>- Huge opportunity to produce not only meat products, but also product other food currently produced by harmful methods with a lower environmental impact | **Low**<br><br>- Cell-based products are not yet commercialised. Although the number of cultured meat companies is growing massively, and the science is now reasonably well-established, there are multiple barriers facing the industry before products can make it to market.<br><br>- It still needs to be proved that cultured meat production can be commercialised at scale.<br><br>- The growth medium is extremely expensive and | **Long term**<br><br>- Barclays predicts that lab-grown real meat, produced from cell cultures, is likely to hit supermarket shelves in a decade<br><br>- Estimated that by 2035, synthetic food can be 10x more efficient than photosynthesis and 10x cheaper than animal food<br><br>- Consultancy AT Kearney predicts cell-based analogues will |

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| | - Opportunity to produce healthier foods | cultured meat production requires high energy use | snare a 35% share of the global meat market by 2040<br><br>- But there are multiple barriers to overcome |
| Controlled environment agriculture and vertical farms | **5**<br><br>-Offers an opportunity to radically change the way we feed the world, providing environment, health and economic opportunities. For example, reduced land-use, saving energy and inputs like fertilisers, reducing waste, guaranteeing supply and self-sufficiency, reducing food miles, more nutritious foods<br><br>- Huge potential environmental benefits: better use of space, fewer food miles, isolation from pathogens, reduction in soil degradation, nutrient and water recapturing and recycling<br><br>- Potential to free up land and return to natural ecosystems, reducing the risk of numerous infectious | **Medium**<br><br>- Vertical farms do exist, but they are mainly confined to the developed world. They are currently only capable of growing high value crops.<br><br>- There are still multiple barriers to overcome to scale up vertical farming and increasing the type of food that can feasibly be grown. For example, the high energy use and infrastructure required | **Medium term**<br><br>- Research shows that, dependent on a few factors, urban agriculture could provide an abundant and varied food supply for the 60% of people living in cities by the year 2030.<br><br>- The global vertical farming market is currently small but projected to expand at a compound annual growth rate of 24.6% between 2019 and 2026. |

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| | diseases spilling over into human populations<br><br>- It could, in theory, supply enough food in a sustainable fashion to comfortably feed all of humankind for the foreseeable future. | | |
| Food sensing and processing tech | **1**<br><br>- Can positively contribute to all three policy goals (improve quality of food, reduce waste and reduce economic losses).<br><br>- Doesn't have any impact on the environmental impact of food production<br><br>- Doesn't do anything to increase financial prospects for farmers | **Medium**<br><br>-The application of hyperspectral imagery is rapidly growing<br><br>-There are still challenges to overcome to make sure the technology is accurate and effective<br><br>- Many food companies are not currently accustomed to reading plots/statistical values, which is needed to correctly operate these technologies | **Medium term**<br><br>- Must overcome challenges on both industrial and technical levels before its full potential can be realised<br><br>- Adoption would require a change in many current procedures, which could take some time |
| Food preservation tech/ nanotech | **1**<br><br>- Can ensure food stays fresher for longer, reducing waste<br><br>- Can also preserve nutritional content of food | **High**<br><br>- Many technologies are already available, but haven't yet been scaled | **Short term**<br><br>- Solutions are already available in stores in some cases. For example, Apeel sciences is a family of plant-derived |

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| | - Depending on the technology, it may not have any impact on the environmental impact of food production | | coatings that can help to keep produce fresh |
| Renewable cold storage | **2**<br><br>- Environmental and economic opportunities, particularly for farmers in low-income countries<br><br>- Could have quite a significant impact on waste, as its estimated that 30-40% of total production is lost before it reaches the market, partly due to lack of proper post-harvest storage<br><br>- Can also help to reduce hunger | **High**<br><br>- The technologies exist, it just needs to be scaled and accessible to all<br><br>- The cost of solar is significantly decreasing | **Short term**<br><br>- It is already in place in many countries. For example, Inspira Farms rolled out super-efficient off-grid cold storage units in partnership with the Rwandan Government and are expected to benefit 100,000 rural smallholder farmers |
| Mobile services and digital marketplaces | **2**<br><br>- Potential to reduce food loss and waste, but not all studies show this is significant | **High**<br><br>- 4% of total investment in the agri-foodtech space was invested in agribusiness marketplaces in 2019 | **Short term**<br><br>- There is a growing number of agribusiness marketplace startups |

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