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GUIDE

Future food system 2050

The global food system, a cornerstone of cultural and economic stability, faces unprecedented pressure to transform over the next two decades. This period will witness more profound changes than the entire 20th century. This thought leadership paper delivers an in-depth analysis of a multitude of interconnected trends and drivers transforming the modern food system. It foresights the likely state of the food system by 2050, providing essential insights for industry, government, academia, non-governmental organisations (NGOs), and research and technology organisations (RTOs), such as the UK's Catapult Network. These insights will aid the formulation of highly competitive and forward-looking innovation strategies that meet the complex challenges of the 21st century.

AUTHORS

Emma York: Technology and Innovation Sustainability Intern
Shak Gohir: Strategic Programmes Manager

From innovation to commercialisation

At CPI we work with partners to translate great ideas into products and processes that enhance health and well-being, protect and improve our environment and increase productivity across industries.

With a deep understanding of innovation processes and funding, outstanding technical expertise and industry relevant assets, we enable products and processes to be quickly and cost-effectively brought to market. This supports the development of next generation manufacturing, highly-skilled jobs and economic growth for the UK.

Foreword

Kris Wadrop, Managing Director of Materials at CPI

Not since the human race transitioned from being hunter-gatherers to farmers, about 10,000 years ago, have we seen such a change in our eating and dietary habits as we have in the past 100 years. The advances in technology (process chemistry, physics, electronics, biology) have enabled unprecedented human population growth that has required a commensurate response in our food supply chain and associated systems.

With the globalisation of markets and the creation of brands, you can buy a Big Mac or KitKat with a Pepsi to wash it down in most countries of the world, and they will ostensibly taste the same. I'm not saying whether that is a good or a bad thing; I'm just saying it's possible.

Large swathes of land that were once tropical rainforests or prairies, home to a biodiverse ecosystem, are now homes to mono-culture farms growing crops such as corn, wheat, or soy, or animals such as cows, sheep, or pigs. Synthetic pesticides and fertilisers are used to minimise pest infestation and maximise crop yield. Most crops grown are used to feed the animals, to provide minimal calories, protein, and nutrients that feed the minority of people. These crops and associated grazing land for the animals occupy 80% of the land used globally for agriculture.

People do not generally associate crude oil with food. Crude oil is associated with heavy industry, energy, and transport fuels, whereas food is "natural"! Most people would be horrified to understand that it takes between 1.5-2 litres of crude oil to deliver an 800-gramme loaf of bread to the supermarket shelf. This oil consumption starts on the farm with drying the seeds before sowing them to grow wheat and finishes in the single-use plastic wrapping the loaf is stored in, keeping it fresh, and that assumes you aren't making toast!

With the projected growth in human population, the greenhouse gas emissions associated with our current food system are not sustainable. Something must change.

Much of the modern health crisis is caused by the food we eat. Ultra-processed, convenience or fast food is dominating our lives. Science has provided sugar, fat, and salt combinations to effectively present food as a stimulant to our bodies, triggering hormonal responses equivalent to many illegal and illicit drugs. Evolution of the human race takes tens of thousands of years; our bodies have no defence against the sugar/fat/salt offensive they have been subjected to over the past century. We have epidemics of obesity, diabetes and heart disease that are crippling our health systems, largely down to our lifestyles and the food we eat.

I've known one of the authors, Shak, as a colleague for several years. I also know he has gone on his own "food journey", learning about the impact of diet on his personal health. As a consequence of that journey, he has become deeply passionate and knowledgeable about the food he eats, the food system in general, its challenges and the opportunities it presents.

As a 50-something desk jockey who keeps active through exercise, I have also been on my own food journey in recent years. I have realised that the quality of food I eat, and as importantly, how I eat it, can have a profound impact on my physical and mental well-being. If it's beige and comes out of a plastic wrapper or box, there is a very high chance it has more than five ingredients, many of which you won't be able to find in your kitchen cupboards. If it's whole food or processed food that would be considered an ingredient, e.g. a can of chopped tomatoes, then it will almost certainly take time to prepare and require some form of cooking. In our fast-paced lives, many of us appear to have lost the art of cooking and, more importantly, the lifestyle of community that comes with sharing a meal with family and friends. How we eat our food, and as importantly, who we eat it with, can have as many health benefits as the food itself.

The following pages present some facts and opinions on how we have got to where we are, and some of the options and changes we need to make to ensure we can address the imbalance that has crept into our food system. The purpose of this publication isn't to make everyone vegan and it's not to shame people into not enjoying a burger or pizza occasionally. The publication's purpose is a call to action, raising your awareness of how the choices you make as a consumer can shape the way the food industry behaves and how those choices can directly impact your health and the health of the planet.

Authors

Emma York: CPI Sustainability Intern

My passion for sustainability stems from its importance in every single part of the economy, affecting industry, the environment, and our society. I am studying Biology at the University of York and currently on my Placement Year at CPI. CPI stood out to me as an innovative company offering opportunities in novel foods and sustainable materials. Through this year, I have been able to explore the sustainability of the food system and analyse complex product supply chains. This research has showcased the extent to which we must rethink and transform how we grow, process, package, distribute, and consume food to ensure we can feed over 9 billion people by 2050 within the planetary boundaries.

Through co-writing this paper, my goal is to inspire stakeholders to embrace transformative change and offer a clear vision of the future food system we must navigate. The solutions we implement today, driven by technological advancements and escalating environmental pressures, will pave the way for a sustainable and prosperous future for generations to come. Despite the significant changes anticipated in our food system, the cultural and social aspects of food will remain af the utmost importance. Food is not just about sustenance; it is a cornerstone of our culture and a vital aspect of community and togetherness, which is fundamental for us to strive to preserve.

Shak Gohir: Strategic Programme Officer

Since CPI's inception in 2004, I have been dedicated to its mission, bringing my background in digitalisation and management consultancy to the forefront of our innovative projects. My journey with CPI has been one of driving transformative change by helping innovators and entrepreneurs bridge the gap between technological potential and real-world application.

The 21st century will witness a profound transformation of the food system. While it has historically provided an abundance of food globally, this achievement has often come at a high cost to the environment, public health, and social equity. The traditional food supply chains have frequently exacerbated environmental degradation, contributed to adverse health outcomes, and perpetuated social inequalities. As we move forward, reimagining this system to address these critical issues will be paramount for ensuring a sustainable, equitable, and healthy future.

This transformation will be a challenging period for many farming communities and incumbent food manufacturers but will represent an enormous opportunity for those who can adapt, and for new entrants who will unlock the opportunities. As with all radical disruptions, the change will likely come from outside the sector. I have co-authored this publication to offer a compass for forward-thinking innovators and governments aiming to formulate successful transformative and competitive strategies.

Purpose of this paper

The global food system, a cornerstone of cultural and economic stability, faces unprecedented pressure to transform over the next two decades. This period will witness more profound changes than the entire 20th century.

This thought leadership paper delivers an in-depth analysis of a multitude of interconnected trends and drivers transforming the modern food system.

It foresights the likely state of the food system by 2050, providing essential insights for industry, government, academia, non-governmental organisations (NGOs), and research and technology organisations (RTOs), such as the UK's Catapult Network. These insights will aid the formulation of highly competitive and forward-looking innovation strategies that meet the complex challenges of the 21st century.

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Executive Summary

Since the Haber-Bosch process was invented in 1913, the food system has undergone a profound transformation. The global production of fertilisers enabled the Green Revolution, leading to major agricultural improvements and increased crop yields worldwide. This provided an abundant supply of crops, vegetables, and fruits for both feed and food. Technological advancements in food processing, energy, and transportation further boosted the productivity of the food system and international trade, allowing foods from different regions and cultures to become available globally.

As a result, the modern food system enabled rapid population growth in the 20th century and played a pivotal role in reshaping society, cultures, and norms. The modern western food system supports many families, workers, and individuals by ensuring easy access to a convenient and plentiful supply of food products at home, work, retail outlets, hotels, restaurants, or on-the-go. This rise in accessibility has facilitated wealth creation across the economy. The ease of accessing prepared and convenient foods has enabled individuals to be more productive at work, and to have more time for leisure activities and social occasions.

However, the modern food system has come at a great expense to the environment, responsible for over 25% of global greenhouse gas emissions and using 70% of available global freshwater. Additionally, it drives 80% of deforestation activities, utilising 38% of the world's habitable land. The food system contributes towards 78% of global ocean and freshwater eutrophication, creating over 500 oceanic "dead zones" where life cannot be sustained. These impacts are accelerating climate change, and are major contributors to global biodiversity loss, threatening the stability of the planet and our future food resiliency.

Exhibit 1 presents a summary of an analysis conducted by CPI, which qualitatively maps some of the environmental impacts of the food system against the nine planetary boundaries. The nine planetary boundaries, pioneered by Johan Rockström, represent the critical quantified thresholds that humanity and our industrial systems must operate within, to preserve the stability and resilience of the Earth system. Transgressing these boundaries increases the risk of large-scale, abrupt, or irreversible environmental changes. Whilst drastic changes may not occur overnight, crossing these thresholds significantly raises risks to people and ecological systems.

The boundaries essentially form the **Earth's ecological ceiling**, and currently six of the nine boundaries have been transgressed. CPI's qualitative analysis reveals that the food system adversely impacts each of the planetary boundaries and highlights how novel foods such as cultivated meat could help to alleviate these pressures.

Planetary Boundaries (Red = Transgressed)	Impacts of Food System on Each Boundary	Environmental Benefits of Cultivated Meat
Climate Change	Food system contributes to over 1/4 global GHG emissions, livestock 14.5% of all human-induced emissions.	Estimated to reduce GHG emissions by up to 96%, due to elimination of methane-producing livestock farming.
Ocean Acidification	25% all CO2 released into atmosphere is absorbed by oceans, affecting marine ecosystems and climate resilience.	Significant lower CO2 emissions, protecting the coral reefs, which are the first climate tipping point.
Land System Change	Agriculture accounts for 80% deforestation activities globally, and utilises 38% of world's land area.	Eliminates deforestation in livestock grazing and feed production. Emphasis on regenerative small-scale farming.
Biosphere Integrity	Intensive monoculture farming and use of synthetic chemicals threatens biodiversity and ecosystem stability.	Opportunity to rewild previously deforested land, promoting return of biodiversity and soil health.
Freshwater Use	Food system contributes 70% of global freshwater withdrawals, livestock contributing to 29% of this footprint.	Significant decrease in freshwater usage by estimated 96%, with no large scale animal feed farming.
Bio-chemical Flows	Agriculture contributes 78% global ocean/freshwater eutrophication, with more than 500 oceanic "dead zones".	Less contamination from fertiliser and manure runoffs. Focus on regenerative farming to promote soil health.
Ozone Depletion	Nitrous oxide is most dominant ozone depletor in atmosphere today, released from fertiliser use and manure.	Significant reduction in nitrous oxide emissions from fertiliser and manure, hence protecting the ozone layer.
Atmospheric Aerosols	Particulate matter released from farming equipment and tilling practices contributes to air pollution.	Less release of particulate matter (e.g. PM2.5, PM10) from farming practices, livestock farming and fertilisers.
Novel Entities	Antibiotics, chemical herbicides and pesticides, and plastics/ microplastics pose risk to public health and wildlife.	Factory farming eliminated, with minimal need for antibiotics. Reduced herbicides/pesticides on smaller farms.

Exhibit 1: Pressures of the food system on all nine planetary boundaries.

Additionally, the modern food system has resulted in social inequalities and divides in many parts of the world such as exploitation of low wage workers, contamination of water systems, and the unintended formation of "food deserts" where access to fresh and healthy foods is difficult. A meta-analysis published in 2024 by British Medical Journal titled "Reasons to Avoid Ultra-Processed Foods" discovered that exposure to these foods can adversely affect up to 32 different health parameters. Since ultra-processed foods have become ubiquitous, the food system has significantly contributed to the rise of chronic diseases such as diabetes type II, certain cancers, cardiovascular diseases, autoimmune diseases, and mental health issues. This in turn is driving up healthcare costs at an unsustainable rate.

These challenges highlight the urgent need for a more sustainable and equitable approach to food production, processing, distribution, and services, necessitating a **Just Transition** to ensure that all stakeholders benefit from the transformation.

By 2050, technological advancements, propelled by Artificial General Intelligence (AGI), will surpass current expectations. AGI will enable AI platforms to perform cognitive activities at human-like levels. Ray Kurzweil predicts that by 2045, society will reach Technological Singularity, driven by Artificial Superintelligence (ASI), leading to unforeseeable technological progress. Thus, foresighting for 2050 necessitates considering at least the emergence of AGI, which will drive rapid scientific discoveries and technological advancements across various domains. This will disrupt traditional practices and result in autonomous farms, factories, and services across all economic sectors, including the future food system. Such facilities are likely to require a much smaller workforce, with the majority of the work being undertaken by robotic equipment and machinery, including humanoid robots, connected to a low-cost AGI Platform. AGI will also accelerate advancements in other domains including energy, materials, nutritional science, and the life sciences.

By 2050, we will be firmly within the Anthropocene epoch, where industrial activities significantly influence the Earth's stability. To preserve this stability and resilience, our industrial complex must operate within the Earth's ecological ceiling. The environmental conditions we will experience in 2050 will depend heavily on how successfully we have addressed climate change. Global temperatures are expected to rise by more than 1.5°C by around 2030, necessitating a global effort to reduce these rising temperatures back below 1.5°C by 2100, by deploying carbon-negative solutions and Nature Positive supply chains. Without significant progress, temperatures could escalate to 2°C or even 3°C by 2100, leading to unprecedented environmental risks and imposing significant costs on human life, the economy, food access, and global security. Thus, we may see the emergence of a commission for planetary stewardship.

By 2050, there will be an abundance of low-cost electrons and energy, which will also enable a transition to sustainable low-cost chemical building blocks and materials. This is likely to be possible through advancements and widespread adoption of wind and solar power, batteries for energy storage, and mass-produced "plug and play" micro-nuclear reactors. Farms will also utilise onsite anaerobic digestion facilities for converting organic waste into biofuels. Micro-nuclear reactors, about the size of a shipping container, will be designed to be stackable and easily distributed to generate onsite electrical energy and process steam as a service. Copenhagen Atomics are currently developing such a reactor system and are targeting the production of green ammonia for manufacturing sustainable fertiliser and shipping fuels. US-based firm Oklo, whose chairman is the CEO of OpenAI, are designing micro-nuclear reactors targeting applications such as AI Data Centres, as well as other industrial facilities.

Between now and 2050, the food system will undergo unprecedented disruption. It will need to provide nutritious affordable food sustainably for over nine billion people, whilst operating within the Earth's ecological ceiling. This transformation will transcend traditional disruptive innovations, propelling a profound and radical shift that will fundamentally reshape how we produce, process, distribute, and consume food. The food system will experience far greater change in the next two decades than it did throughout the entire 20th century. This transition will be a challenging period for many farming communities and incumbent food manufacturers but will represent an enormous opportunity for those who can adapt, and for new entrants who will unlock the opportunities. As with all disruptions, the change will likely come from outside the sector as external innovators often bring fresh ambitions and perspectives, novel technologies, new expertise, and different business models that challenge established norms and drive transformative shifts.

Intensive factory livestock farms will rapidly decline by 2050, however many existing medium- and small-scale farms will still likely remain. This will involve adapting practices to be more regenerative, focusing on protecting soil health, implementing polycrops and permaculture practices, and enhancing biodiversity. Farmers will leverage alternative business models and utilise advanced digital technologies including autonomous machines, drones, and robotic sheepdogs, to improve profitability and efficiency. This shift will enable farmers to integrate precision agriculture into their farms, minimising the use of fertilisers, antibiotics, and pesticides. Transitioning to these sustainable practices will enable farmers to continue to operate successfully within the future food system, protecting the prosperity of the farmland for future generations, and reducing wider environmental impacts.

This publication comprises of three key parts:

- **Part I: Trends and Drivers Reshaping the Food System:** The first part of this paper identifies and discusses 37 trends and drivers that are reshaping the food system, as summarised in *Exhibit 3*. These have been grouped into four areas: 1) Social and Economic Factors; 2) Environmental Issues and Crises; 3) Scientific and Technological Advancements; and 4) Changing Geopolitical Landscape.
- **Part II: Fore sighting the Future Food System:** The analysis of these trends and drivers has then been leveraged to forecast the likely shape and characteristics of the food system in 2050, which is discussed in the second part of this publication. For quick reference, *Exhibit 2* below summarises 30 key features of the future food system in 2050, segmented into four thematic areas: 1) Overarching Technological Advancements; 2) Agriculture, Livestock, and Fishing; 3) Food Processing and Distribution; and 4) Consumer Preferences and Experience.
- **Part III: CPI AgriTech and Novel Food Case Studies:** In the final part of this paper, we provide some examples of CPI case studies, paving the way towards the future food system through our expertise in biomanufacturing, formulation, process scale-up, and emerging technologies.

Exhibit 2: Features of the future food system in 2050

Overarching Technological Advancements

1. Abundant Supply of Low-Cost Energy with Solar, Wind, Micro-Nuclear Reactors and Biofuels
2. Transition to Safe, Sustainable & Circular Materials, including the "Magic Nine" Chemical Building Blocks
3. Nature Positive Supply Chains Operating within the Earth's Ecological Ceiling
4. Engineering Biology for Agritech, Precision Fermentation, and Cellular Agriculture
5. Autonomous Systems, Drones, Robotics, and Humanoid Robots, with Minimal Human Workers
6. "Plug and Play" AGI-Powered Digital Platforms and Internet of Thinking Things (IoTT)

Agriculture, Livestock, and Fishing

7. Sustainable Production of Fertilisers, Pesticides, Packaging, and Alternative Feeds
8. Autonomous and Regenerative Crop, Vegetables, and Orchard Farming
9. Precision Agriculture for Targeted Application of Fertilisers, Pesticides, and Weed-killing Lasers
10. Rise of Smart Indoor and Vertical Farming Providing Fresh Produce to Urban areas
11. Regenerative Livestock Farming with Methane-Reducing techniques and Robotic Sheepdogs
12. Decline of Intensive Livestock Factory Farming, with many small-scale farmers adapting
13. Rise of Smart Sustainable Aquaculture utilising Advanced Health Monitoring
14. Strict Regulations and Monitoring of Wild Fishing using Robotic Vessels and Drones

Food Processing and Distribution

15. Autonomous Food Processing Factories efficiently producing more nutritious food products.
16. Precision Fermentation of Food Ingredients and Dairy Products
17. Production of Alternative Proteins including Plant-based, Fungi, Algae, and Insects
18. Production of Cultivated Meat, Fish, and Dairy, disrupting existing industries
19. Digitalisation with empower small-scale niche manufacturers to compete within large markets.
20. Enhanced In-Store Shopping Experience, including use of Smart Augmented Reality Glasses
21. Online Virtual Reality Metaverse Stores providing a platform for Brand Positioning
22. Efficient Delivery of Groceries and Takeaways by Autonomous Vehicles, Drones, and Bots

Consumer Preferences and Experience

23. Rise of Ultra-Personalised Wellness and Nutrition Consumer Services
24. Decline in Demand for Ultra-Processed Foods that can impact negatively on Public Health
25. Reduced Meat and Dairy Consumption, with many alternative options readily available
26. New Category of Foods and Services for enhanced Healthspan and Longevity
27. Incorporation of "Food as Medicine" into Medical Care Plans by Healthcare Professionals
28. Robotic Autonomous Kitchens at Home and in Commercial Settings
29. Novel Kitchen Appliances including 3D Printers, Indoor Growing Units, and Mini Meat Bioreactors
30. Interactive and Immersive Restaurants and Smart Robotic Servers

Our modern food system is being reshaped by a multitude of interconnected social, economic, environmental, technological, and geopolitical trends and drivers.

Part I: Trends and Drivers Reshaping the Food System

> Our modern food system has provided us with an abundance of food worldwide, yet it also contributes significantly to the prevalence of chronic diseases, leads to substantial biodiversity loss, acts as a major driver of climate change, and frequently perpetuates social inequalities along its supply chains. Addressing these challenges demands a Just Transition for all.

Food and culture are intrinsically intertwined, reflecting the rich tapestry of global diversity and heritage, and bringing people together. This vital aspect of food within society must be protected during the food system transition, as it is critically threatened by unification and westernisation. Around the world, culinary traditions serve not only as a means of sustenance but also as a profound expression of cultural identity, social customs, and historical evolution. Each region's unique ingredients, cooking techniques, and food rituals reveal the historical narrative of its people, their environment, and their interactions with other cultures, offering a flavourful journey through the world's varied and vibrant gastronomic landscapes. This symbiotic relationship between food and culture underscores the role of cuisine in shaping our understanding and appreciation of global communities and their histories.

It is a dynamic that will continue to shape the future food system and one that will come under rising pressure as the global food production system transforms. *Exhibit 3* shows the comprehensive landscape of the multifaceted forces shaping the future food system comprising of: Social and Economic Factors; Environmental Issues and Crises; Scientific and Technological Advancements; and the Changing Geopolitical Landscape. The modern food system has delivered an unprecedented abundance of affordable food, underpinned by the Haber-Bosch process to enable production of synthetic fertiliser. This has significantly increased crop yields and laid the foundation for the Green Revolution, boosting food supply.

Global supply chains fundamentally transformed the food industry, revolutionising how food is produced, processed, distributed, and accessed. They have vastly broadened the range of convenient food products available to consumers, significantly enhancing food availability across various regions. However, this advancement has not come without its drawbacks. The system faces substantial challenges and complexities, particularly concerning planetary scale environmental crises, huge disparities in food equity along supply chains, and the escalating prevalence of chronic health conditions that can be linked directly to dietary choices and their subsequent impact on rising healthcare costs. Addressing these challenges demands a Just Transition, ensuring that the move towards a more sustainable and equitable food system benefits all stakeholders including consumers and the more vulnerable.

Exhibit 3: Dynamics, trends and drivers shaping the food system

Social and Economic Factors

- Demographic Changes
- Dietary Shifts and Cultures
- Food Equity and Security
- Awareness of Ultra-Processed Foods
- Rising Level of Food Allergies
- Rising Level of Chronic Disease
- Rising Health and Social Care Costs
- Rise of Food as Medicine
- Personalised Nutrition

Environmental Issues and Crises

- Climate Change
- Ocean Acidification
- Land System Change
- Loss of Biosphere Integrity
- Biogeochemical Nutrient Flows
- Freshwater Usage
- Stratospheric Ozone Depletion
- Atmospheric Aerosol Loading
- Release of Novel Entities

Scientific and Technological Advancements

- Sustainable Energy and Materials
- Robotics and Autonomous Systems
- Nutrition and Longevity Science
- Metaverse, VR, & AR
- Advanced Genetics
- 3D Printing and Bioprinting
- Precision Fermentation
- Regenerative Agriculture
- Cellular Agriculture
- Vertical Indoor Farming
- Alternative Proteins
- Cloud, Data Pools, and Digital Twins
- Web 3.0 and Blockchain
- Artificial Intelligence

Changing Geopolitical Landscape

- Reshaping Globalisation
- Planetary Stewardship
- Subsidies, Policies, and a Just Transition
- Conflicts and Food Insecurity
- Food Labelling and Regulation

Our global food system will need to increase production by 50-70% for 2050 to meet the health and nutritional needs of over nine billion people.

Social and Economic Factors

Social and Economic Factors

- Demographic Changes
- Rising Health and Social Care Costs
- Dietary Shifts and Cultures
- Rise of Food as Medicine
- Food Equity and Security
- Personalised Nutrition
- Awareness of Ultra-Processed Foods
- Rise in Food Allergies
- Rising Level of Chronic Disease

Summary

- Food trends are largely influenced by culture and religion, with the UK offering a selection of global cuisines reflecting cultural diversity within society. Many recent food trends have been shaped by rising consumer awareness of health, nutritional, and environmental impacts of the foods they eat.
- The United Nations anticipates the global population to reach 9.8 billion by 2050, necessitating a 50-70% increase in global food production.
- Africa will experience 57% of this global population growth, and opportunities may arise from their rapidly increasing young population and abundance of natural resources.
- Many countries will experience an ageing population, notably China, with a drastic decrease in rural farmers, marking the need for more autonomous farming systems.
- Global food supply chains contribute to inequalities and labour exploitation, exacerbating economic disparities and food insecurity.
- One third of the global population did not have access to adequate nutritious food in 2020, affected severely by conflict and rising environmental pressures.
- Food deserts and the cost-of-living crisis are worsening access to food not just internationally, but within many regions of the UK, especially for families.
- By 2035, two-thirds of adults over age of 65 will be managing multiple health conditions, placing an unsustainable pressure on NHS, largely attributed to the rise in ultra-processed foods.
- Personalised nutrition services, such ZOE and InsideTracker, are paving the way for gut-friendly diets and preventative health monitoring, which will be integrated into the future healthcare system.
- Food as medicine is already being adopted, to help prevent and reverse chronic conditions, such as heart disease.
- The significant rise in allergies, with 615% increase in food-induced anaphylaxis between 1992-2012, highlights the need for innovative allergy management approaches and personalised nutrition as a potential tool for reducing allergy prevalence.

Global food production will need to increase by 50-70% by 2050, to feed the growing global population. Essential to this is ensuring a "Just Transition", whereby food production can be increased for meeting the nutritional needs of populations in a sustainable way, whilst also ensuring that no one is left behind during this shift. Notably, the United Nations anticipates a significant global population surge, reaching approximately 9.8 billion by 2050, 10 billion by 2055, and further escalating to 11.2 billion by the close of the century in 2100. The population of the United Kingdom is following a similar trend of population rise, expected to reach 70.49 million by 2030, followed by an increase to 74.08 million in 2050 and 78.05 million by 2100. Due to the uneven distribution of this population growth globally and its resulting demographic changes, different countries face opposing challenges and opportunities for the future food system. This variation underscores the importance of finding the most equitable ways to navigate these dynamic shifts.

Approximately 95% of global population growth will take place in low- and middle-income countries, and Africa will account for 57% of this growth (1.4 billion people). This can be attributed to high fertility rates coupled with declining child mortality in Africa. In particular, the population of sub-Saharan Africa is projected to double by 2050. Today, 60% of Africa's population is under the age of 25, making Africa the world's youngest continent[1]. With greater levels of political cohesion and an abundance of natural resources, this provides Africa with the opportunity to drive forward new innovative farming methods and a more sustainable crop production system[2].

In tandem, a notable demographic shift is underway in many developed regions, marked by an ageing population and a concurrent decline in the number of young individuals as shown in *Exhibit 4*. This trend is also occurring in some developing nations, especially pronounced in China, where the population is expected to drastically drop from 1.4 billion to potentially as low as 525 million by 2100, according to the Shanghai Academy of Social Sciences. This is largely due to the historical one-child policy and rapid urbanisation. Urbanisation trends have not only resulted in migration to cities, thereby straining rural labour resources, but also transforming agricultural land use for urban expansion, further challenging food security and farming efficiency. Projections indicate that China's elderly population will surpass its working-age population around 2080, posing substantial challenges for food security, agricultural sustainability, and economic stability. A study noted that in 2019, rural ageing in China led to a 4% reduction in farm size, primarily due to land ownership transfers and land abandonment (around 4 million hectares). Older farmers, often hesitant to adopt new farming techniques, contributed towards this trend, resulting in lower crop yields and financial difficulties.

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[1] Cities Alliance, The Burgeoning Africa Youth Population: Potential or Challenge? 2020
[2] UN Report, Africa's youth finds its power in transforming food systems, 2021

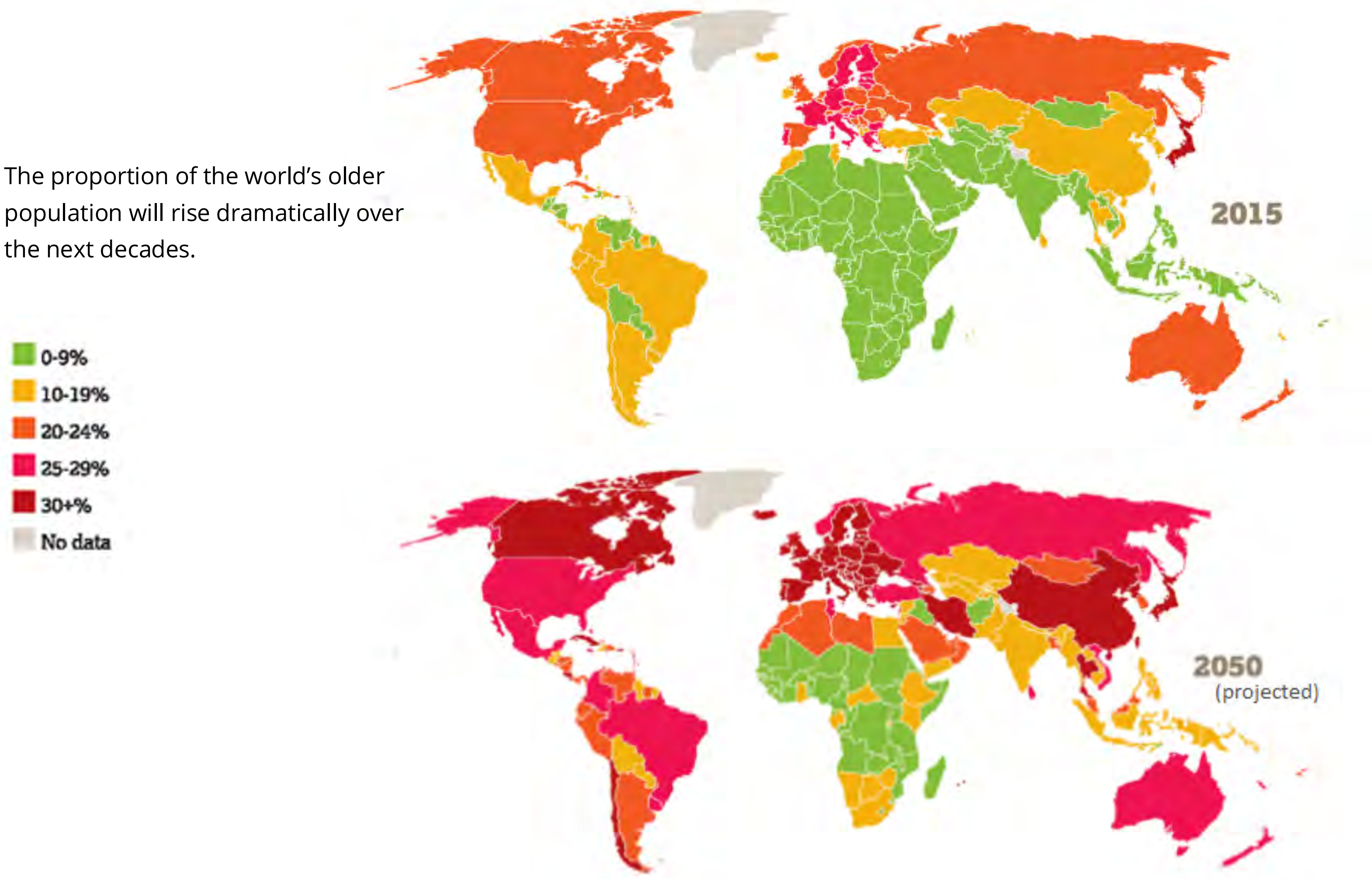

Exhibit 4: Proportion of the world's ageing population worldwide projection for 2050.

Image credit: Office for National Statistics, living longer: how our population is changing and why it matters. United Nation Population Fund and website https://www.unfpa.org/

In response to these demographic changes, the future of farming is set for a radical overhaul, pivoting towards advanced technology and automation to enhance efficiency. This evolution is particularly crucial in areas like China, where the agricultural workforce is dwindling. The adoption of robotics and autonomous systems will be instrumental in mechanising agriculture on a large scale, essential for supporting a growing global population. We are already witnessing the initial phases of these technological advances. Transitioning to a more automated, efficient, and sustainable farming model is a strategic solution to both demographic shifts and the increasing need for agricultural productivity.

Both of these examples of opposing demographic shifts between Africa and China showcase the potential pressures on the current global food system, which will need to massively evolve to successfully adapt to changing population dynamics. Many regions across the globe, including both developing and developed nations, are experiencing widespread problems in food equity and security, due to rising pressures on the food system and socio-economic factors.

Our current food system contributes to many inequalities and labour exploitation across the supply chains, particularly in less affluent countries. For example, in 2021 the United Nations estimated that globally there are more than 160 million child labourers, 70% of which are working in the agriculture sector[3]. Many of these children are forced to work in poor conditions for long hours with little pay, to support their families and meet basic needs. Child labour is closely linked to rising food inequity and insecurity within developing nations, which is further exacerbating global economic disparities. Addressing problems in access to nutritious food within these nations is essential for preventing future child labour within the food system. Furthermore, the global food system relies on many developing nations to supply essential food commodities; therefore, it is paramount for the future food system to address these social concerns for transparency, fairness, resilience, and sustainability.

The 2023 Global Report on Food Crises[4], published by the United Nations, highlights that regions like Africa are today facing acute and deep challenges regarding food security and access, exacerbated by conflict, and both economic and environmental shocks. Nearly one in three people globally (2.37 billion) did not have access to adequate nutritious food in 2020[5]. If current trends within the food system continue, food insecurity and malnutrition will lead to an estimated 640 million people underweight by 2050, including 121 million children, particularly affecting populations of India, Southeast Asia, and sub-Saharan Africa[6]. Food security hinges not only on

[3] FAO Food Security, nutrition, and ending child labour in agriculture, 2021.
[4] Global Report on Food Crises, United Nations, May 2023
[5] FAO State of Food Security and Nutrition in the World, 2021
[6] UN Food System Economic Commission Report

access to ample amounts of food, but also on its nutritional value and safety. Achieving nutrition security is crucial for the health and wellbeing of populations globally, as it provides a balanced diet with essential nutrients for preventing physical and cognitive diseases. As global populations grow and climate challenges intensify, it becomes increasingly vital for our food systems to evolve, addressing these disparities and striving to supply healthy, nutritious, and accessible foods to communities and nations worldwide.

Developed nations are not exempt from food security challenges. In countries like the UK, for example, food banks operated by charities are progressively becoming essential services for many communities. Reported food bank usage has steadily increased since June 2021 (9%), with 15% saying they used a food bank in March 2022[7]. This trend is indicative of escalating concerns regarding food affordability and the prevalence of food deserts. Access to affordable nutritious food options is increasingly becoming a significant hurdle for many people and families living in low-income areas. A total of 9.3 million adults in the UK experienced food insecurity in January 2023, according to the Food Foundation, which is around 17.7% of all households. This has been further worsened by the cost-of-living crisis in recent years, with many people, especially families, struggling to meet basic needs. Reports in 2022 show that almost one in four consumers (22%) reported skipping meals, or cutting portion sizes due to financial struggles, and this trend has risen steadily since June 2021. Government initiatives, such as free school meal programs that offer support to vulnerable families, are critical in enhancing food security in developed nations, especially in areas with limited access to affordable, healthy foods.

Food security and equity also heavily depend on the resilience of global food supply chains, which is crucial in mitigating food price volatility and preventing global food shortages. This becomes even more critical amidst the challenges posed by climate change and the increasing occurrence of extreme weather events. Such climate shifts not only influence where in the world certain foods can be grown, but also exacerbates the risk of crop failures and subsequent price surges. Future food systems must therefore incorporate climate resilience into agricultural practices, ensuring robust domestic supplies and diversified, reliable global trade networks that do not depend excessively on any single country. With the looming threats of climate change, conflicts and resource wars may escalate, further impacting food security and supply chain resilience. The globalisation of the supply chain, exemplified by the UK's diverse food imports, contributes to a more resilient system by broadening the variety of food sources available, essential for ensuring food security and equity are maintained.

[7] FSA Household Food Insecurity Main Report, 2022

In the UK, the culinary landscape is marked by a rich diversity of cuisines and foods, offering consumers an extensive array of choices. This variety stems not only from the globalisation of food supply chains but also from immigration trends, religious practices, cultural influences, and shifting consumer preferences. Globalisation has opened doors to a wide range of food products from across the globe, fuelling a growing appetite for international flavours and prompting supermarkets and restaurants to expand their selections. Immigration has played a significant role in this diversification, with individuals bringing their culinary traditions to the UK, thereby enriching the food market. For instance, by the early 2020s, Tesco, one of the UK's leading retailers, was stocking over 300 Polish products in more than 500 stores, underscoring the supermarket's adaptation to cater to diverse consumer demands. This craving for diversity is further driven by consumers' quest for authentic culinary experiences, inspired by travel and a curiosity to explore new tastes. Additionally, food choices are deeply intertwined with religion, culture, and tradition, for example demand for halal and kosher foods, and demand spikes for certain culturally significant foods during religious and festive periods. The evolution of the future food system will be shaped by religious and cultural considerations, especially with the introduction of novel foods like cultivated meat, which must meet varied dietary laws and preferences.

Although food trends are profoundly influenced by cultural preferences and consumer demand, the future food system must also proactively address the health implications of dietary choices. By focusing on enhancing the nutritional value of foods available to the public, we can work towards alleviating the pressures on healthcare systems and promoting overall societal well-being, whilst maintaining cultural diversity in food cuisines. In recent years, **UK consumers have been shifting away from meat and dairy consumption**, with a 2021 report highlighting that British meat consumption dropped by 17% over the past decade[8], alongside a rise in diversity of choices for plant-based meat alternatives available within retail outlets. This shift has been catalysed by a rising awareness of the health implications and environmental issues associated with meat, alongside the burden of the cost-of-living crisis. The public is urged to reduce meat intake by up to 30% over the next decade in line with the UK government’s national strategy to reduce meat consumption, which aims to significantly alleviate the adverse impacts of meat on both public health and climate change.

In the UK, the prevalence of multimorbidity has rapidly increased and is projected to rise significantly in the coming decades, placing a significant burden on the NHS budget. By 2035, it's estimated that two-thirds of adults over the age of 65 will be managing multiple health conditions, with 17% grappling with four or more diseases,

[8] UK public now eating significantly less meat, BBC News 2021

marking a doubling of the rate observed in 2015[9]. This not only strains the healthcare system, but also impacts social care costs and quality of life of individuals affected. Currently, we are seeing more of these diseases in young adults and children, and this is largely due to the rise of ultra-processed foods in the food system, especially in developed countries such as the USA and UK. Ultra-processed foods (UPFs) classified as NOVA-4 are characterised by their heavy processing, high saturated fat and sugar content, and addition of additives, such as emulsifiers, stabilisers, preservatives and colourings, and constitute approximately half of the average UK family's diet. This escalating consumption of UPFs, a trend not confined to developed countries but observed globally, has been paralleled with rising obesity rates and the prevalence of other nutrition-related chronic diseases[10].

For instance, a randomised trial revealed that high UPF intake is linked to a 23–51% greater risk of obesity and significant associations with cardiovascular diseases, where the consumers with high intake of UPFs faced a 29% greater risk of cardiovascular mortality. Furthermore, the risk of developing type 2 diabetes was 44–65% higher among those with the highest UPF consumption levels. Notably, every 10% increase in UPF intake was associated with a 12–15% greater risk of diabetes, a 33% increased risk of depression, and an 11% rise in breast cancer risk. These alarming statistics underscore the urgent need to transition away from UPFs towards healthier, less processed food options, a critical step for reducing the burden on healthcare systems and improving global nutrition and health outcomes. The Food Foundation's 2022 Broken Plate report highlights that metabolic conditions cost the UK approximately £74 billion every year in direct NHS costs, lost workforce productivity and reduced life expectancy[11]. These costs are rising and unsustainable, leading to substantial strains on our healthcare system.

To reduce global consumption of UPFs, regulation and policies will need to be implemented, such as sugar taxes, front-of-package labelling, marketing restrictions (especially with children's foods), and targeting school meals for nutritional regulation. A recent paper highlighted that food companies face the challenge of re-engineering these affordable convenient UPFs in a way that a) promotes gut health, b) protects the liver, and c) supports the brain[12]. These measures would lead to a more preventative approach to healthcare, by reducing the causes of chronic disease from a dietary and lifestyle perspective, to reduce subsequent hospital admissions and ongoing health and social care costs.

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[9] NIHR Multi morbidity predicted to increase in UK over the next 20 years, 2018.
[10] Global Food Research Program, Ultra-processed foods a global threat to public health, 2021
[11] The Broken Plate 2022 Report, Food Foundation
[12] The Metabolic Matrix, Re-engineering UPFs to feed the gut, protect the liver, and support the brain, 2023

The rising awareness of the health impacts of UPFs has been significantly driven by the emergence of nutritional education platforms. For instance, ZOE has become a pioneer in providing accessible personalised nutrition to consumers, with at-home glucose monitoring, gut microbiome testing and science-led educational nutrition podcasts. These tests empower individuals to make informed dietary choices tailored to their unique health needs and mark a pivotal shift in how the public engages with nutrition and health. This heightened awareness and knowledge of personal health impacts has driven changes in the food system itself, with surging demands for healthier food options such as fermented foods, higher fibre products, and plant-based alternatives. Notably, ZOE's launch of its kefir "gut shot" drink—rich in live cultures and free of the additives found in competitor products—underscores the growing consumer emphasis on microbiome health. There has also been a rise in popularity of high-end functional wellness foods such as AG1, which offer nutritional benefits towards gut health and the immune system. Demand for these gut health products, even with a premium price, highlights the increasing consumer awareness of the importance of diets in our health and wellbeing.

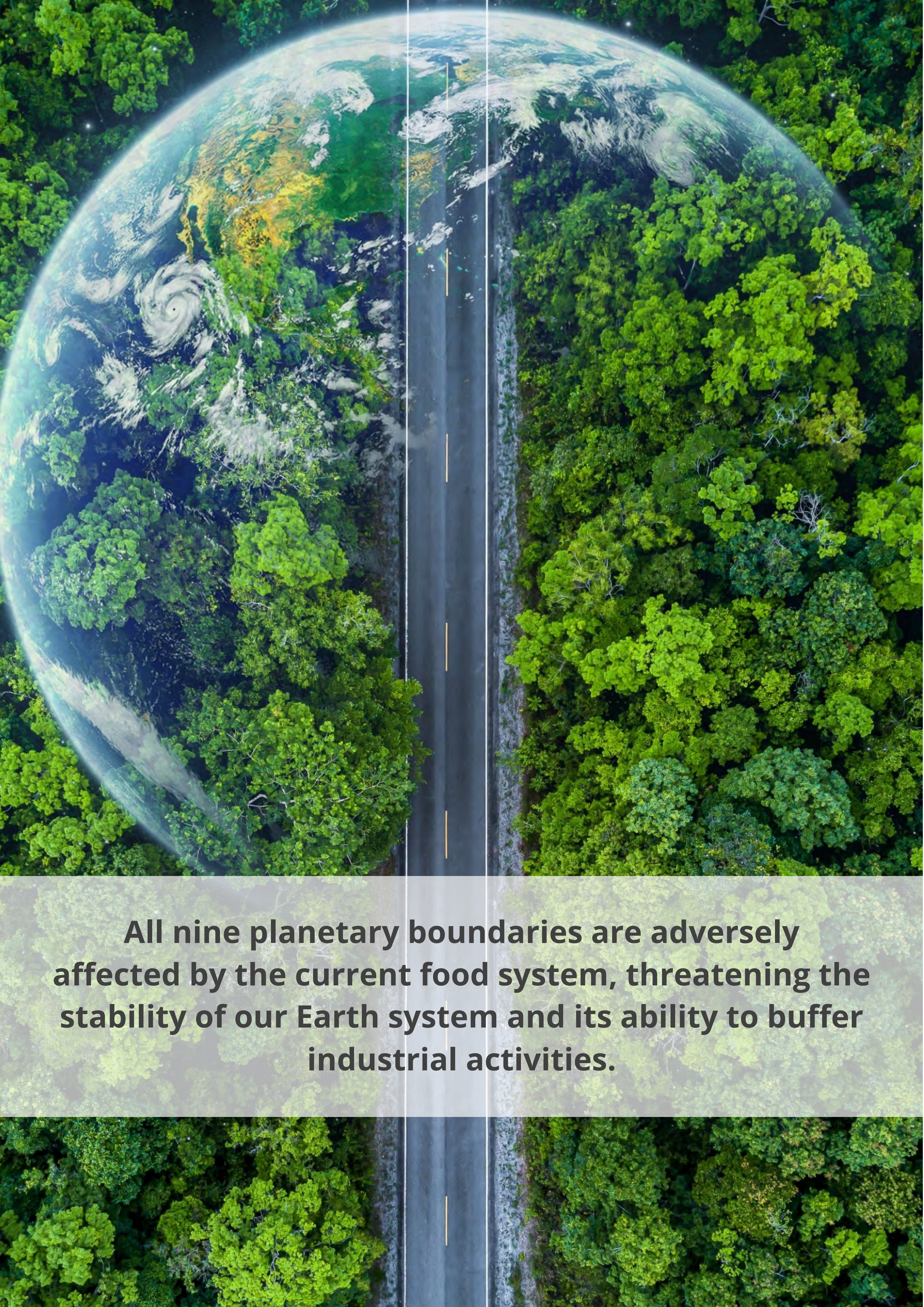
This shift towards personalised nutrition offers an opportunity for integration of these diagnostics into the healthcare system, for prevention and treatment of many chronic non-communicable diseases. This would form part of a transition to functional lifestyle medicine, a patient-centred healthcare model providing a holistic approach with integration of diet and other lifestyle factors into disease treatment. An individual's diet massively influences their health outcomes, with the gut microbiome being heavily linked to the immune system and metabolic pathways. A diverse microbiome could reduce an individual's disease symptoms through personalised dietary modifications, highlighting the importance of utilising personalised nutrition for a "food as medicine" approach within healthcare.

Food as medicine could significantly decrease healthcare costs by reducing the number of patients with the leading chronic diseases. For example, in the Lancet study in 1990, lifestyle changes including a low-fat vegetarian diet not only halted the progression of coronary heart disease but reversed the disease severity. Patients had an average 7% reduction in coronary artery plaque after a year, with nearly 40% reduction in chest pain after another five years. Another study, published by "Diabetes Care" in 2018, demonstrated that personalised dietary interventions led to 40% of participants achieving remission of Type 2 Diabetes after six months, highlighting the potential for tailored nutrition in reversing chronic conditions. Diets play a massive role in the development of non-communicable diseases and are thus important as part of the treatment and remission of those diseases.

In recent years there has been a significant rise in food allergies, including nuts, milk, eggs, soy, wheat, and fish, necessitating adaptations within the food industry.

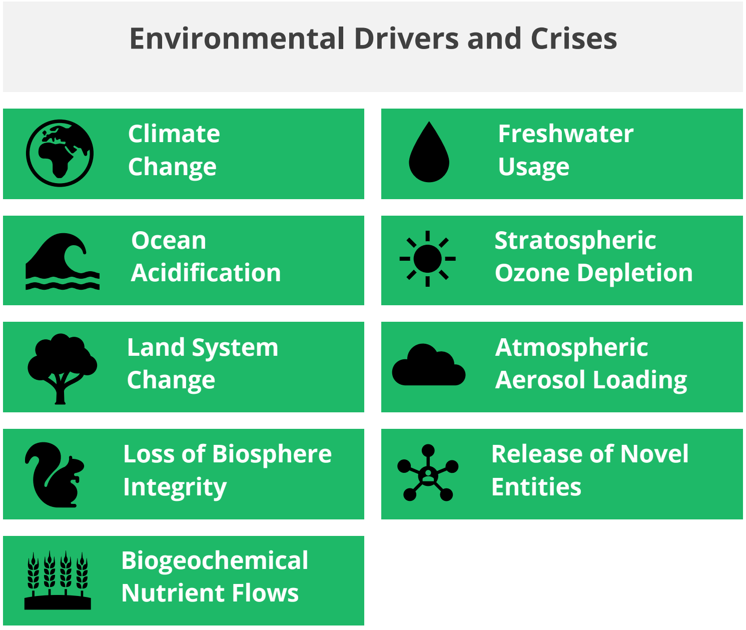
Allergen management measures have included increased transparency with incorporation of clearer allergen labelling, allergen enquiries in restaurants, and an increase in availability and variety of “free from” food options. This rise in food allergies is multifaceted, with potential links to the individual’s gut microbiome, which plays a role in modulating the immune system response and autoimmunity. The UK has seen notable increases in food allergy prevalence, with hospital admissions for food-induced anaphylaxis rising by 615% between 1992 and 2012[13], underscoring the need for innovative approaches to allergy management. Personalised nutrition and gut microbiome testing emerge as promising tools in this context, offering insights into the complex relationship between specific gut microbes and the development of food allergies. By understanding these interactions, researchers and healthcare providers can explore novel dietary strategies and treatments aimed at modulating the gut microbiome to prevent or mitigate allergic reactions.

[13] Increase in anaphylaxis-related hospitalizations but no increase in fatalities: an analysis of United Kingdom national anaphylaxis data, 1992-2012, Turner et. al 2014.



All nine planetary boundaries are adversely affected by the current food system, threatening the stability of our Earth system and its ability to buffer industrial activities.

Environmental Drivers and Crises



Summary

- The nine planetary boundaries represent the critical thresholds we must operate within to preserve the stability of Earth System, upon which human life depends.
- Six of the nine boundaries have currently been transgressed, and the current food system adversely impacts all nine boundaries, especially meat and dairy production.
- Food system contributes to one third of global GHG emissions, including methane released by livestock, food waste, and rice cultivation, which is a short-lived GHG but 30x more potent than CO_2.
- Ocean acidification is leading to the first climate tipping point with risk of 70-90% loss of tropical and subtropical coral reefs at 1.5°C temperature rise.
- Agriculture accounts for 80% of global deforestation, occupying 38% of the world's land area including half of the world's habitable land.
- Agriculture threatens 86% of species currently at risk of extinction, affected by extensive monocultures, chemical-use, deforestation, and habitat loss.
- Agricultural runoffs, especially livestock manure, contribute towards 78% global ocean and freshwater eutrophication, severely affecting quality of freshwater in the UK, e.g. River Wye and Lough Neagh.
- Global food system is responsible for 70% of global freshwater withdrawals, primarily for excessive crop irrigation, and livestock hydration and sanitation.
- Nitrous oxide, released from fertilisers and manure, lingers in the atmosphere for 114 years, is 300 times more potent than CO_2, and poses new threat to the ozone layer.
- Fine particulate matter released from diesel powered farming equipment, tilling practices, livestock waste and synthetic fertilisers are contributing to air pollution affecting human health and local ecosystems.
- Novel entities including plastic and microplastics pose a threat to marine life, with estimated more plastic than fish in the oceans by 2050, and to human health, with recent study finding microplastics in 80% of human blood samples tested.

The Nine planetary boundaries, defined by leading scientists over the past 20 years, represent the critical thresholds within which humanity must operate to preserve the stability and resilience of the Earth System, essential for our survival and well-being. These boundaries act as control variables of the Earth System in the Anthropocene, offering humanity the ability to remain in a Holocene-like state that can sustain human life. Currently six of the nine planetary boundaries have been transgressed, contributing towards risk of destabilising the Earth System, threatening ecological balance and the future viability of our planet. The sustainability of the food system critically depends on adherence to these boundaries, for reliable food production as we currently know it. The planetary boundaries[14] are depicted in *Exhibit 5*.

Critically, the stability of our planet and its ability to withstand climatic changes depends significantly on the health of both our biosphere and oceans. Together, they absorb 50% of carbon dioxide released into the atmosphere, acting as buffers to climate change. However, increasing pressures on these natural systems are diminishing their capability to mitigate these environmental shifts effectively, and subsequently the Earth's climate resilience. These natural systems are heavily interconnected, with each planetary boundary transgression posing further escalation to the other boundaries, due to negative feedback loops reinforcing the decline in the Earth System stability. Therefore, it is paramount that we evolve the future food system to protect and restore the planetary boundaries within the safe operating space to prevent further environmental risks.

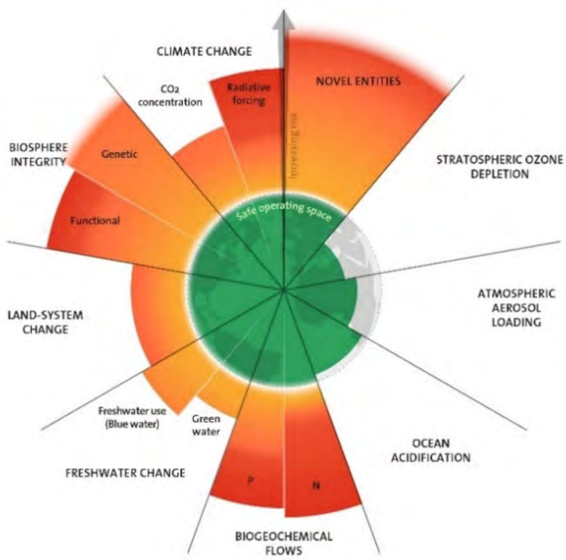


Exhibit 5: Planetary boundaries 2023

Image credit: Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023

1. Climate Change: The food system contributes to one-third of the global GHG emissions[15], with livestock farming alone responsible for approximately 14.5% of all human-induced emissions worldwide[16]. Therefore, without addressing the food system we cannot tackle the escalating global climate crisis. These GHG emissions include carbon dioxide, methane and nitrous oxide. The food system contributes massively to increasing atmospheric carbon dioxide concentrations, through activities such as large-scale deforestation, high energy-use, and extensive food miles. Adopting renewable

[14] Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023
[15] Nature Food, Food systems are responsible for a third of global anthropogenic GHG emissions, 2021
[16] The World Bank, Moving towards sustainability: the livestock sector and the world bank, 2021

energy sources and transitioning to electric vehicles within the sector are essential steps towards minimising these impacts. Furthermore, 35% of GHG emissions from the food system are methane, constituting 60% of global methane emissions, mainly resulting from livestock farming, food loss and waste, and rice cultivation from flooded rice paddies [17]. Methane is shorter-lived in the atmosphere remaining for around 12 years, but is 30 times stronger than carbon dioxide, contributing to between 10-15% of global warming. Reducing the release of methane into the atmosphere, for example by reducing the scale of livestock farming, is critical for reducing the acceleration of climate change. Another major factor in the food system's emissions is the use of fertilisers and manure, which emit nitrous oxide, a gas that lingers in the atmosphere for 114 years and possesses a global warming potential 300 times greater than carbon dioxide. Effective lower impact farming could provide significant reductions in the release of nitrous oxide, and enhance carbon storage within soils, reducing the food system's overall impact on the climate change planetary boundary.

2. Ocean Acidification: Rising atmospheric carbon dioxide levels are not only exacerbating global warming but are also contributing to ocean acidification, diminishing the Earth's resilience to climate change and its ability to act as a climate buffer. Around 25% of all carbon dioxide released into the atmosphere is absorbed by the oceans, substantially affecting marine life and ecosystems. Changes in marine ecosystems can lead to major shifts in fish distribution, which could reduce catch potential in tropical countries by as much as 40% by 2050[18], impacting on livelihoods and food security. If current trends continue, the first climate "tipping point" is likely to be reached, with substantial loss of the coral reefs and further escalation of more climate change tipping points.

The Intergovernmental Panel on Climate Change (IPCC) warns that 70-90% of tropical and subtropical coral reefs are at risk of disappearance at approximately 1.5°C above pre-industrial temperatures, with almost total loss expected at 2 °C. According to IPCC's recent findings, surpassing the average 1.5°C threshold by the early 2030s appears increasingly likely across all emission scenarios, with a record number of days breaching the 1.5°C threshold during 2023[19]. However, there is hope that swift and significant reductions in GHG emissions could reverse this trend, curbing temperature rise back below 1.5°C by the end of the century. To combat this impending global temperature rise, the focus must extend beyond merely decarbonising the food system. It is crucial to adopt a "nature-positive" approach, which includes capturing atmospheric carbon and rewilding lands to restore biodiversity and environmental balance.

[17] Climate Works Foundation, Reducing Methane Emissions in the Global Food System, 2024
[18] Nature: Climate Change, tropical fisheries, and prospects for sustainable development, 2020
[19] World breaches key 1.5C warming mark for record number of days, BBC News, 2023

3. Land System Change: The concept of rewilding and adopting "nature-positive" practices is particularly relevant within the context of land system change, a boundary currently transgressed due to extensive land clearance. Agriculture is the main driver of global deforestation, accounting for around 80% of these activities. Notably, the Amazon Rainforest has seen vast areas cleared for cattle ranching and soy cultivation, resulting in loss of an extensive carbon sink and diminishing biodiversity. The Food and Agriculture Organisation (FAO) reported that as of 2020 agriculture occupies around 38% of the world's land area, including half of the world's habitable land. This extensive land use significantly impacts soil quality and health, lowering the land's capacity to sequester carbon from the atmosphere. Reductions in meat production would significantly lessen the strain on land systems, paving the way for the restoration of deforested areas. This, in turn, would enhance ecosystem resilience, boost biodiversity, and strengthen carbon sinks, contributing to a more sustainable and balanced land system. Deforestation has also had major impacts on UK temperate forests and woodlands, which have vanished overtime due to human activities. Alarmingly, 73% of the remaining fragments of these UK forests lack official protection, leaving them vulnerable to threats such as overgrazing, pollution and invasive species. Action must be taken to preserve and restore these biodiverse forests within the UK, which are becoming increasingly rare.

4. Biosphere Integrity: The United Nations has identified the global food system as the leading contributor to biodiversity loss, with agriculture threatening 86% of species currently at risk of extinction[20]. This alarming statistic highlights the urgency to transform land systems to foster the regeneration of diverse ecosystems essential for the recovery of global biodiversity. The production of animal feed plays a substantial role in the transgression of biodiversity limits, characterised by extensive monoculture practices, excessive application of chemical pesticides impacting non-target species, and the clearance of previously species rich ecosystems for agricultural expansion. Over-use of fertilisers and pesticides can also contribute towards a decline in soil biodiversity and long-term health, by causing soil acidification. Mining for fertiliser components is also a significant contributor towards these ecological challenges, causing habitat fragmentation, chemical pollution of nearby waterways, and release of dust and aerosols into the local atmosphere. A shift towards more regenerative agricultural practices is essential for reducing the burden of mining and detrimental land system change on biodiversity losses.

Biodiversity loss is also occurring within our oceans, with 90% of global marine fish stocks being overfished, endangering the survival of 1093 fish species and bycatch, by

[20] UNEP, Our global food system is the primary driver of biodiversity loss, 2021

not allowing them to naturally regenerate[21]. These harmful overfishing practices have been driven by increased global demand, illegal fishing activities, and the prevalence of harmful subsidies which do not incentivise more considerate fishing practices [22]. The traceability of wild fish stocks, from ocean to plate, will be important in the future food system for minimising these impacts. Furthermore, sustainable aquaculture, if done properly, could prevent overfishing and act as a solution for supplying larger amounts of fish to our population, whilst maintaining the health of ocean ecosystems.

5. Phosphorus and Nitrogen Flows: The biogeochemical flows boundary has also been transgressed, impacted by nutrient runoffs from over-fertilised farmland, contributing towards eutrophication and harmful algal blooms, which cause a decline in aquatic life and local water quality. In fact, agriculture contributes towards 78% of global ocean and freshwater eutrophication. There are currently more than 500 “dead zones” within global oceans, where marine life cannot survive in the low oxygen conditions, leading to declines in fish populations and affecting stability of the aquatic ecosystems. This not only impacts on local food and water security, but also on the livelihoods of locals relying on fishing and tourism industries. A stark example is Lough Neagh in Northern Ireland, the UK's largest freshwater lake, which has suffered from toxic algal blooms and a significant decline in aquatic life due to agricultural pollution and runoffs, including from pig farms[23]. This has adversely impacted wildlife, the fishing industry, tourism, freshwater supplies, and the health of local residents. Given that Lough Neagh provides approximately 40% of Northern Ireland's drinking water, the contamination poses a substantial threat to water quality and security, underscoring the urgent need for effective management of agricultural runoffs.

More recently, the River Wye, stretching across England and Wales, has seen similar pollution and expansion of algal blooms, 70% of which has been contributed to agricultural runoffs[24]. Expansions of chicken farming within the river catchment area has contributed massively to this, with nitrogen and phosphate rich chicken manure being used as an organic fertiliser. Regulation and investments in more sustainable farming practices must be implemented to reduce this detrimental water pollution, and its impacts on fish supplies, water quality, and biodiversity.

6. Freshwater Use: Moreover, the global food system is responsible for 70% of freshwater withdrawals worldwide, with the livestock sector alone accounting for 29% of this water footprint, contributing to the transgression of the freshwater use boundary. This extensive water usage is primarily allocated to crop irrigation, and livestock hydration and sanitation, underscoring the substantial environmental footprint of our

[21] Overfishing drives over one-third of all sharks and rays towards a global extinction crisis, 2021, Dulvy et al.
[22] Overfishing, WWF 2023
[23] Carbon Brief, Lough Neagh: How climate change intensified toxic algae on the UK’s largest lake, 2023
[24] BBC, River Wye, Government in court over chicken poo in River Wye, 2024

current agricultural practices. Our food system depends upon freshwater in all aspects; therefore, water insecurity can lead to food insecurity. Improvements in water-use efficiency, water recycling, and measures to minimise water contamination would reduce this burden of our food system on water resources, and result in a more sustainable future production system for the growing global population.

7. Stratospheric Ozone Depletion: In the 1980s, thinning of the ozone layer by ozone depleting substances (ODS) such as chlorofluorocarbons (CFCs), for example from fridges, allowed increased UV radiation to reach Earth, posing threats to human health and ecosystems. Due to implementation of the Montreal Protocol of 1987, one of the most successful global environmental agreements in history, over 98% of controlled ODSs were eliminated, significantly restoring the stratospheric ozone layer. However currently in the 21st century we face a new and increasing threat to the ozone layer. Nitrous oxide[25], released from agricultural practices including fertiliser use, burning of fossil fuels, and industrial processes, is the most dominant ODS in the atmosphere today. Nitrous oxide is threatening the stability of the ozone layer, and, unlike CFCs, is not regulated by the Montreal Protocol. UK's Department for Environment Food & Rural Affairs (DEFRA), estimated in 2022 that 69% of all nitrous oxide emissions are from the agricultural sector[26]. Transformation in energy use, fertiliser use, and manure management are needed within agriculture to reduce impacts on nitrous oxide emissions, thus preventing further damage to the ozone layer, to avoid negative health impacts on humans and wildlife.

8. Atmospheric Aerosol Loading: As well as impacting on ozone depletion, agricultural emissions also impact on air pollution levels. Atmospheric aerosol loading refers to the release of particulate matter into the atmosphere, which can be generated via secondary reactions of ammonia emissions with NOx and sulphur dioxide in the atmosphere. According to the "Nature Food" journal in 2021, agriculture contributes up to 12% of total PM2.5 fine particulate matter released in the UK, for example from diesel powered vehicles, tilling practices, livestock waste, and synthetic fertiliser use. Particulate matter results in the generation of regional air pollution, which can affect human health and local ecosystems. Adoption of regenerative farming practices such as "no-till" farming, and the use of less industrial equipment and fertilisers on farms could reduce these emissions and promote soil health and productivity of the farmland.

9. Novel Entities: Reducing the use of chemicals within farming can also reduce impacts on the novel entities' planetary boundary, which is threatened by the release of synthetic substances into the environment, such as antibiotics, herbicides, pesticides, plastics and microplastics. These novel substances pose threats to biodiversity, human

[25] Science, Nitrous Oxide: Dominant Ozone-Depleting Substance Emitted in the 21st Century, 2009
[26] Department of Environment, Food and Rural Affairs, Agri-climate report 2022

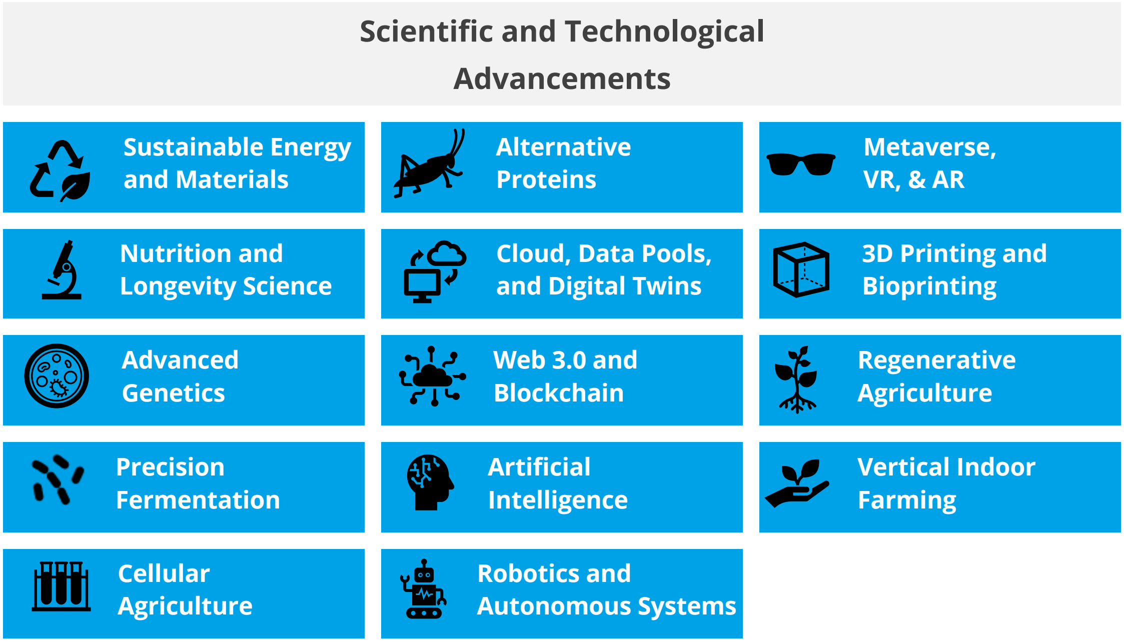
health, and ecosystem stability. A pressing concern is the rise of antibiotic resistance, exacerbated by the overuse of antibiotics in industrial livestock production. Public health concerns are further compounded by the use of synthetic chemicals such as pesticides contaminating the foods we consume, potentially disrupting the human gut microbiome, a key defender of our immune system. Another alarming impact of novel entities has been highlighted by Dame Ellen MacArthur, who warns that by 2050 there may be more plastic than fish in the oceans, impacting severely on our marine ecosystems and food security[27]. The environmental release of plastics and microplastics from single-use food packaging not only impacts on marine life, but is subsequently accumulating within the food chain, finding its way back to humans. A ground-breaking study published in Environment International in 2022 revealed that microplastics were found in 80% of human blood samples tested, marking the significant health threats we currently face from plastic pollution[28], and the need for the food system to discover safe effective alternatives to current plastic food packaging.

All nine planetary boundaries are closely interconnected, as shown by the complexity of the interactions between the food system and various environmental crises. The interdependent nature of these boundaries highlights a profound risk to the stability of our planet, posing substantial threats to our food production system. The detrimental impacts of our current food system on these boundaries are likely to reverberate, intensifying global environmental challenges that, in turn, circle back to further strain the food system itself. To navigate this complex challenge, investments in innovative technological solutions will be crucial to mitigate and reverse planetary boundary transgressions, ensuring sustainability of the future food system is reached.

[27] World Economic Forum, The New Plastics Economy Rethinking the future of plastics, 2016
[28] The Guardian, Microplastics found in human blood for first time, 2022

Scientific advancements and technological innovation over the coming two decades will revolutionise the ways we grow, produce, and consume foods.

Scientific and Technological Advancements



Summary

- Exponential digital technologies are moving towards AI Singularity by 2045 which, combined with digital twins, humanoid robotics, blockchain, and the metaverse, will revolutionise the energy, materials, healthcare, and food sectors.
- Over the next two decades, the global economy will undergo an energy transition towards renewable and nuclear energy, that will affect every single sector of the economy, including the food system.
- We will move towards more renewable, sustainable and circular materials, reducing reliance on fossil fuels, to sustainably produce the “magic nine” chemical building blocks we rely on for 96% of product materials.
- Personalised nutrition apps with in-depth AI-driven analysis are influencing consumer choice and the rise in demand for functional and health foods.
- Advanced genetics are being used to enhance the nutritional profile and environmental resilience of crops, and to programme the microbes for precision fermentation applications.
- Cultivated meat is emerging as a sustainable way to produce real meat from animal cells, with current barriers in scalability, cost, consumer acceptance and regulation, that can be readily addressed.
- Alternative proteins are being explored globally to tackle climate change, including plant-based, fungi, algae, and insects, with differing levels of acceptance.
- 3D printing offers customisability of designs, nutrition, and textures, from custom-made cakes to the bioprinting of meats, and will become a staple appliance in kitchens.
- Regenerative farming practices focussed on protecting soil biodiversity are key to long-term sustainable farming and are likely to challenge existing intensive farming methods.
- Urban vertical and indoor farming is advancing and will serve as a vital source of fresh foods all year round for densely populated regions and food deserts.

Transition to clean low-cost energy and sustainable materials

Between now and 2050, the energy sector will experience a comprehensive shift towards sustainable low-cost electrons and fuels, driven by the urgent need to address climate change and other escalating environmental crises, such as biodiversity loss. As the scale and frequency of climate-related events intensifies, challenging the status quo of business operations will become essential, thus prompting demand for innovative solutions for resiliency and sustainability. This transition will span a diverse array of renewable and sustainable energy sources, such as wind, solar, nuclear, wave, hydrothermal, geothermal, geological hydrogen, and biomass, signifying a critical shift towards eco-friendly and sustainable low-cost energy solutions worldwide.

Recent exploration activities in the United States and Australia have led to the discovery of geological hydrogen stores beneath the Earth Surface, and it is estimated that there are currently 5.5 trillion tons of geo-locked hydrogen. Geological hydrogen is generated in large quantities when certain iron-rich minerals react with water. Requiring no electrolysis or steam reforming, geological hydrogen could become a low-cost source of sustainable energy and material feedstocks. In contrast, current projections for Nuclear Fusion suggest that its commercialisation may occur in the later part of this century. However, small-scale modular reactors (SMRs) for nuclear energy, including thorium-based reactors, will emerge within the next few years, offering scalable secure and safe energy generation. By 2050, the availability of low-cost micro-nuclear reactors, the size of a single shipping container that can be mass produced in factories, is a real possibility with innovative start-ups such as Oklo and Copenhagen Atomics leading the way forward. These **micro-nuclear reactors** would be able to supply low-cost energy to industrial facilities such as large data centres, manufacturing plants and even cities.

Smart grids, localised generation, electrification, battery technology, geological and green hydrogen, and synthetic fuels will serve as foundational components by 2050, facilitating access and use of these sustainable energy resources. This shift will act as a catalyst for the electrification of an extensive array of agricultural machinery and food processing equipment. This in turn will deepen digitalisation, resulting in a host of smart devices on farms and in factories, such as robots, drones, and autonomous tractors. For the clean energy transition to be successful it must result in an abundance of low-cost clean electrons to enable the production of low-cost chemicals and materials for downstream sectors to harness, including the food production-consumption system.

By 2050, progress in renewable and nuclear energy sources will significantly limit the utilisation of fossil resources, primarily confining their use to deriving chemical building blocks. The extend to which fossil resource use will decline is currently difficult to determine and visualise, due to deep invested interest by incumbent stakeholders and our day-to-day reliance on existing fossil powered infrastructure, mobility, and products. The climate crisis is already impacting “business as usual” and its impact will set to accelerate. This will yield competing approaches for boosting resource efficiency and producing chemicals and materials, including agrichemicals, feed, and foods.

Currently, 96% of the material composition in today's products are based on the "**magic nine"** chemical building blocks: ammonia, ethylene, propylene, butylene, butadiene, benzene, toluene, xylenes, and methanol, originating from oil and gas processing, as shown in *Exhibit 6*. These chemicals permeate every aspect of our daily lives, facilitating the creation of an extensive range of materials, such as plastics, packaging, pesticides, fibres, fertilisers, and rubber. In response to the climate crisis, industrial stakeholders are actively investigating and developing low-cost sustainable alternative routes and methods, including:

- **Sustainable production of fossil-based chemicals** using carbon capture, utilisation, and storage (CCUS), or even full electrification of fossil supply chains dedicated for manufacturing of only the “magic nine” chemical building blocks, hence eliminating the need for most CCUS facilities.
- **Sustainable production of fossil-free chemicals** and materials incorporating carbon captured direct from air, green and geological hydrogen, sustainable biomaterials, and biotechnology capabilities.
- **Shift towards circular economy principles** extending product life, reuse, recovery, and recycling to retain the value of finite materials (such as metals, minerals, and plastics) and renewable materials (such as biomass sources) for longer within the economy. For the future food system this will mean the use of circular machinery (equipment that can be remanufactured, and recycled), and circular packaging.

The adoption of alternative production methods of the “magic nine”, alongside the integration of renewable and sustainable energy sources, will alleviate the strain that industrial activities place on the nine planetary boundaries. This approach combined with waste elimination and reduction will help reverse overshoots and ensure that the global economy can operate within the Earth's ecological ceiling, fostering a sustainable balance with our planet's finite and renewable resources. This will play an important role in planetary stewardship by 2050.

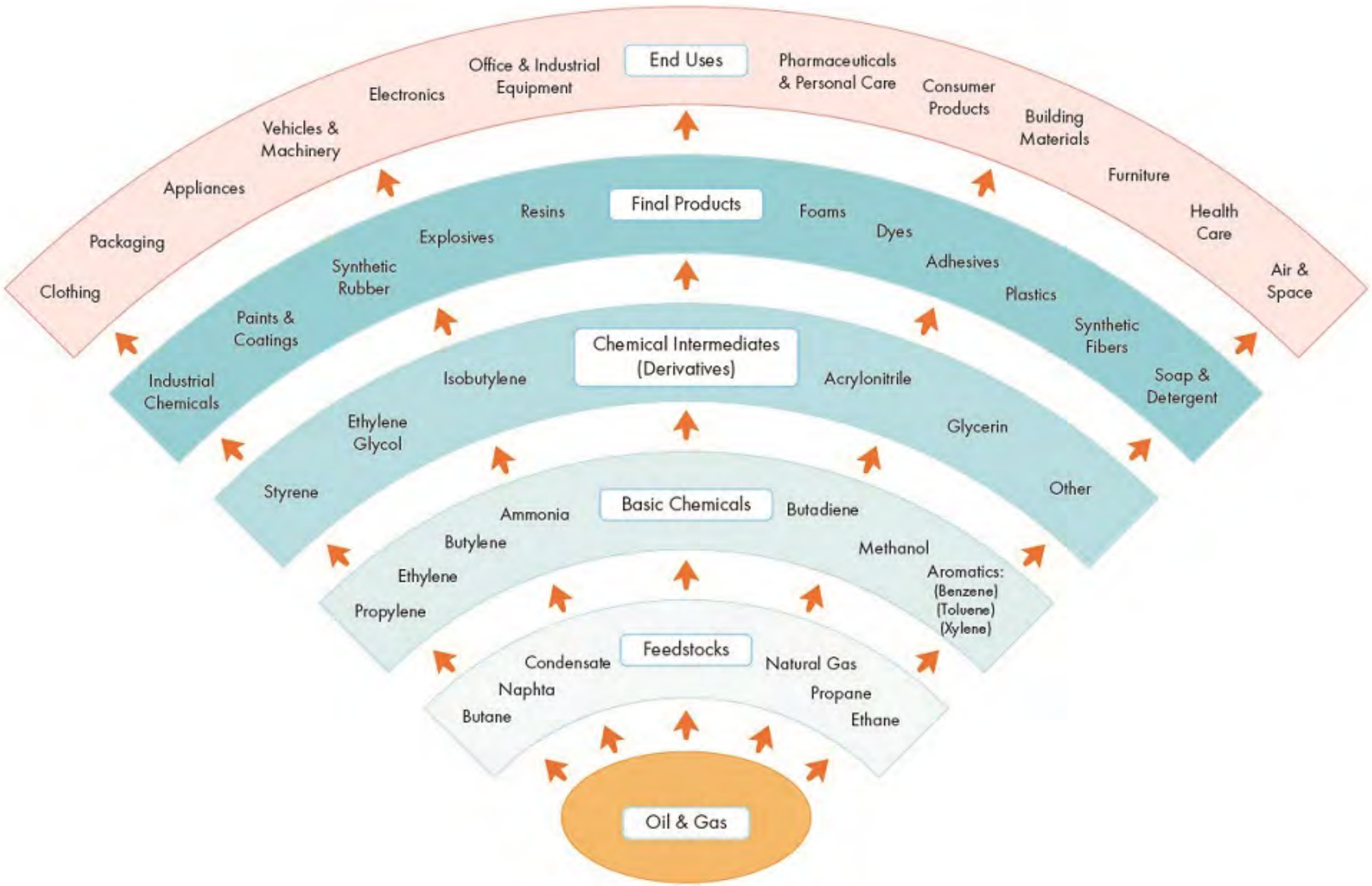


Exhibit 6: The "magic nine" basic chemical building blocks for today's economy

Source: Canada Energy Regulator, Market Snapshot: Petrochemical products in everyday life, [CER Website]

Advancements in Nutrition and Longevity Sciences

Advancements in nutritional and longevity science are impacting not just medical healthcare, but also the future food system. Longevity science is a new and emerging branch of the life sciences. It is making groundbreaking advancements in comprehending the molecular, cellular, and physiological mechanisms responsible for establishing and preserving health. It delves into the human body's innate biochemical mechanisms that maintain health, such as how the body prevents the emergence of cancer, and how the body repairs damaged cellular structures, proteins, and DNA.

This innovative approach diverges from traditional methods that primarily focus on intervening in biochemical mechanisms after the disease and its symptoms have taken hold. Longevity science is focused more on staying healthy, reversing biological ageing, and extending both health and lifespan. In today's ageing population the longevity movement is growing. This movement impacts healthcare, skin aesthetics, fitness, and the food industry. Indeed, as people live healthier for longer, every aspect of the economy will be impacted. For food industries, scientific advancements in nutrition, medical and longevity science will open the door to:

- **Ultra-personalised wellness and nutrition services for health optimisation:** Imagine AI-powered apps analysing your gut microbiome profiling, blood tests, DNA profiling, biological age, body weight and composition, activity data, sleep data, and other attributes. Such apps are already emerging, and can generate lifestyle recommendations, such as food combinations, fasting, meal timings, exercise plans, and supplementations based upon a person's unique biology and response to foods. These applications are today influencing and changing consumer behaviour and choices. Early-stage firms, such as InsideTracker[29] in the United States, is offering just a service to US-based customers. They offer regular blood test services profiling over 48 different blood biomarkers and the ability for customers to connect their wearable smart watches, rings, and bands. Well before 2050, similar firms could be offering not just food recommendations

[29] Inside Tracker, Live Healthier Longer

and plans, but also food ordering, preparation, and delivery services at a click, tailored to the health needs of individuals. It holds the potential to disrupt existing online and high street channels for food shopping and will allow consumers to determine the price of food from both a financial and health perspective.

- **Specialised functional foods and nutraceuticals**: Beyond standard vitamins and minerals, future functional foods may incorporate longevity bioactive compounds such as: resveratrol, curcumin, epigallocatechin gallate, spermidine, nicotinamide riboside, or specific gut bacteria strains shown in studies to promote longevity. Targeted novel bioactive ingredients for novel foods and supplements can readily be manufactured using precision fermentation, to reduce costs and improve its environmental sustainability footprint. Imagine healthy yoghurt enriched with longevity-promoting microbes, dark chocolate with specific flavonoid concentrations, or a supplement designed to boost Nicotinamide adenine dinucleotide (NAD+) levels, to slow ageing, prevent disease onset, and aid recovery from illnesses. Newcastle-based start-up Nuchido already offers such an NAD+ booster supplement, formulated based on longevity science. Additionally, product ProLon is a precision nutrition technology clinically proven to keep your body in a fasting state whilst nourishing your body with food over a five-day period. This helps to rejuvenate the body triggering biological processes such as autophagy and even stem cell production. ProLon has been established by Dr Valter Longo, the Director of the Longevity Institute at the University of Southern California.

  Another example of a recently released longevity food range is the Blueprint Stack, launched by Bryan Johnson. He is the most biologically quantified individual in history and a professional in rejuvenation athletics, holding a prominent ranking in the Rejuvenation Olympics. With a team of thirty medical scientists and doctors, Bryan Johnson has spent £2M per year fine tuning his daily longevity regiment, known as the Blueprint Protocol, for rejuvenating and reversing his own inner biological age. Every ingredient and supplement he consumes has been rigorously researched and then evaluated by the impact it has on his biomarker profile and biological age over time. Recently, Bryan Johnson introduced his inaugural line of longevity-focused food products, named the Blueprint Stack, which are available for anyone to purchase online.

- **Decline in the consumption of ultra-processed foods (UPFs):** As we move towards the future food system, health and nutrition services will reveal to consumers the adverse impact certain foods have, such as ultra-processed foods, on their health status and lifespan. Producers of such foods are likely to see a decline in demand for their products overtime, as health apps provide transparency of consumer's food choices on their long-term health and wellbeing. One of the future risks will be the formation of social divides if access to these apps and services are not affordable for the general population. Hence, by 2050 it will be important for individuals in society to have access to affordable healthy foods, as well as low-cost personalised health and nutrition apps.

- **Longevity science has introduced the concept of biological ageing** and the rate of ageing using methods such as DNA methylation testing. These tests hold significant potential for evaluating the impact of different foods, including ultra-processed foods and novel foods, on long-term health by assessing their effects on a person's biological age. As more individuals adopt personalised nutrition plans supported by AI-powered apps, data on the influence of specific diets on biological ageing will naturally begin to emerge. Consequently, as people live healthier lives for longer, their eating habits are likely to undergo significant transformations. Regulators could potentially use a combination of methods in the future to assess the impact of novel foods or indeed ultra-processed foods on biological ageing and the gut microbiome. This approach would help determine the associated risks and health benefits of new foods, allowing regulators to make more informed decisions about their safety and efficacy.
- **Food as medicine is rapidly gaining traction** as both healthcare professionals and consumers increasingly recognise the profound impact of diet on health and well-being. A notable advocate of this approach is Dr Dean Ornish, whose pioneering work has demonstrated the potential of intensive lifestyle changes, including dietary interventions, to reverse heart disease. Dr Ornish's studies have shown that a low-fat, plant-based diet, combined with exercise and stress management, can not only prevent but also reverse the progression of cardiovascular disease. Additionally, his recent clinical research and trials have shown that early-stage Alzheimer's disease (AD)[30] in many cases can be addressed through intensive lifestyle and dietary interventions. The research concludes that around 30-50% of Alzheimer's Disease cases are likely to be preventable because their causes are linked to risk factors that can be modified. According to Dementia UK, Alzheimer's Disease affects 1 in 14 people over the age of 65, and 1 in 6 people over the age of 80. Complementing such dietary interventions, the advent of digital health devices enables medical professionals and patients to monitor their nutritional intake, track health metrics, and personalise their dietary plans, further integrating the "food as medicine" concept into medical practice. As research continues to unveil the intricate connections between nutrition and disease, "food as medicine" will become an integral part of medicine.

[30] Effects of intensive lifestyle changes on the progression of mild cognitive impairment or early dementia due to Alzheimer's disease: a randomized, controlled clinical trial, Dean Ornish et al, June 2044, BMC

Biotechnology, Precision Fermentation, and Advanced Genetics for Food Production

Biotechnology will play an increasingly critical role in the innovation of future food ingredients. It involves the harnessing of biological processes used to produce useful products for a wide range of industries including healthcare, food, agriculture, materials, manufacturing, and biofuels, and has significantly shaped the food system for centuries. The use of fermentation dates back to around 6,000–7,000 years ago. Today, fermentation is widely conducted within large-scale bioreactors, often with the addition of specific microbes, including yeast and bacteria. These are able to produce a wide range of everyday foods including beers, wines, cheese, breads, vinegars, tofu, miso, sauerkraut, black teas, and even processing cacao beans for chocolate. Likewise, selective breeding dates back thousands of years, giving us all of the plants, fruits and livestock, we consume today.

Advancements in biotechnology, including agricultural biotechnology and precision fermentation will continue to shape the foods we consume, boosting food production, productivity, and supply in an environmentally sustainable manor for a growing global population. Notably technologies including gene editing, gene transfer, gene silencing and synthetic biology are beginning to evolve the food system beyond traditional methods such as selective breeding. These advancements are able to enhance the capabilities of precision fermentation, holding the promise to radically disrupt the food system and alter the status quo.

Selective breeding, a practice that has been used for thousands of years, has shaped our current food system by enhancing yields and the productivity of crops and livestock. For example, selective breeding between 1960s and 2005[31] reduced the days to acquire 2kg of chicken meat from 100 days to 40, and increased eggs per tonne of feed by 80%. In recent years, this traditional method has been assisted by the emergence of Marker Assisted Selection technology (MAS). This technology allows for the screening and precise selection of desired plants, animals, and microbes by their genetics using molecular markers, rather than relying on observable characteristics. The use of

[31] Livestock 2.0 – genome editing for fitter, healthier, and more productive farmed animals, 2018

molecular markers allows researchers to identify specific traits at the embryonic or seed stage, bypassing the need for organisms to mature to an observable state, thereby improving the results of selective breeding programmes. Although selective breeding has been very successful in enhancing our crops and livestock, advanced genetic technologies are emerging as a new way of enhancing organisms within the food system. These technologies span from precise incremental DNA base changes, to transferring and silencing of genes, and even extending to the design and printing of completely novel genes, engineered by computer software.

CRISPR-Cas9, discovered in the early 2010s, offers precise DNA base editing across a broad spectrum of organisms. By enabling specific, targeted modifications without the need to introduce foreign DNA, this ground-breaking technology has accelerated the development and implementation of genetically enhanced crops for addressing food security and climate change challenges. Gene editing via this technology has already produced commercialised GABA tomatoes developed by Japanese Start-up Sanatech Seed[32]. These tomatoes have enhanced levels of GABA, which promotes relaxation and lower blood pressure, promoting consumer health. The company aims to launch many more edited fruits, vegetables, and even fish in the future. As well as being adopted to enhance plant characteristics such as disease resistance, reduced allergenicity, enhanced nutrition, and extended shelf life, CRISPR-Cas9 also has applications in the production of biofuels, and sustainable materials and chemicals, to reduce the environmental burden of industrial processes.

Beyond the realm of gene editing lies the advanced field of genetic modification/engineering, a technique where beneficial genes are transferred from one organism to another, resulting in a transgenic GM organism with desired traits and outputs. This technology has significantly contributed to the food system over the last few decades by further enhancing crop yield, nutritional value, and resistance to pests and other environmental pressures. For example, staple crops including corn, soybeans and rice, have been engineered to withstand herbicides and produce their own insecticides, thereby reducing the need for chemical inputs. Moreover, genetic engineering holds the promise of addressing critical global challenges such as food security and climate change adaptation by creating crops that can grow in varied and changing environmental conditions. GMOs can also enhance the nutritional benefits of certain crops, especially in countries struggling with malnutrition. As this field evolves, it continues to spark debate over biosafety, transparency, patents, seed ownership, ethics, and food labelling. However, its potential to revolutionise food production and contribute to sustainable agriculture remains undeniable.

[32] GABA-enriched tomato is first CRISPR-edited food to enter market, Nature 2021

Current fermentation practices are fundamental in producing a wide array of food ingredients and products, including meat analogues, through three main types of fermentation: traditional, biomass, and precision fermentation[33]. Traditional fermentation is the oldest form, leveraging natural processes and microbes to enhance flavour, preserve food, and increase the nutritional value, as seen in yoghurt, cheese, and sauerkraut. Biomass fermentation represents a more recent development and involves the rapid growth of microorganisms, such as fungi used in Quorn products, to efficiently produce large quantities of protein-rich food within bioreactors. This method is particularly advantageous for generating substantial amounts of edible biomass in a controlled environment.

The most advanced type, precision fermentation, specifically modifies microbes to produce targeted proteins and ingredients that are then extracted and purified for use in specific food products. This technique does not involve the consumption of the microbes themselves, but focuses on the isolated components they generate, allowing for the creation of highly specialised and sustainable food ingredients. For example, microbes have been genetically engineered to produce animal-free dairy proteins, such as casein and whey, enabling production of dairy alternatives that match nutritional and sensory profiles of traditional dairy, without the associated environmental footprint. Furthermore, genetically engineered microbes can produce ingredients for meat alternatives, for example Impossible Foods who have used precision fermentation to produce Heme protein to enhance the meaty taste of their plant-based burgers.

Precision fermentation has recently been harnessed for the **production of egg replacements**. For example, in 2023 the first animal-free ovalbumin protein, the main protein found in egg whites, was produced by precision fermentation, acting as a successful replacement to the functional properties of egg white powder[34]. This can be utilised as an ingredient within everyday food products sold in supermarkets, including cakes. Furthermore, The Every Company has harnessed this technology to produce the world's first precision fermented "liquid egg", which can be used for scrambled eggs, omelettes, and home baking[35]. Although we are yet to see a whole egg replicated, current capabilities in this space could significantly reduce reliance on chickens for egg production for food ingredients, and commercial or home cooking in our future food system.

Precision fermentation also has applications in nutrient and vitamin production, for example omega-3 fatty acids like EPA and DHA, which can now be produced using engineered algae and yeast, rather than sourcing from fish oils. This innovation not only

[33] Good Food Institute, Fermentation Guide, 2024
[34] Fast Company, The eggs of the future will be from precision fermentation, 2023
[35] Vegconomist, The EVERY Co. Unveils The EVERY Egg, World's First Precision Fermentation Liquid Eggs, 2023

reduces the burden on marine life, but also offers vegetarians and vegans with an accessible source of this essential nutrient. Genetic engineering is already transforming the food system and is likely to continue to do so. In the future, synthetic biology may be incorporated to extend the outputs we are able to generate from microbes. This would enable a “food-as-software” approach to food production, where an infinite number of proteins and molecules could be produced at speed and scale via precision fermentation, for designing foods in ways we currently cannot imagine.

Synthetic biology goes beyond genetic engineering by redesigning organisms with entirely new biological functions not previously found in nature, involving the design and printing of novel genes via computer programming. This facilitates rapid engineering of new genomes, which could contribute to future sustainability solutions within the food system by enhancing crops, facilitating production of novel foods, and offering environmental remediation applications. However, this powerful technology has sparked debates over safety and regulation, more so than genetic engineering, due to the production of completely novel sections of DNA. We must evaluate the potential risks of these novel technologies, before implementing them at scale, and assess this against their vast array of opportunities for sustainable food production.

Currently, RNA interference (RNAi) is an emerging biotechnology approach that could improve crops without genetic modification, by using RNA molecules to influence the translation of certain proteins, to turn on/off gene expression. RNAi is a natural process within plants where protein expression is inhibited via a feedback mechanism. For example, RNAi has been applied in corn to produce molecules that target and deter the Western Corn Rootworm, effectively serving as a natural pesticide. The versatility of RNAi technology extends beyond pest resistance, with potential applications in improving nutritional profiles, extending shelf life, and increasing environmental stress tolerance of crops. This emerging technology could revolutionise the ways we produce foods, whilst ensuring that the resulting products are safe and align with regulations.

Many of these novel processes within genetic engineering and modern biotechnology face scepticism, and may be controversial in many countries, due to the impacts on key stakeholders including farmers, with associated issues of patents and crop ownership. Therefore, although advanced genetics provide vast opportunities for food security, enhancing nutrition, and tackling climate change, we must address the ways in which this technology is distributed and controlled, to ensure fairness and equity, and to protect the livelihoods of farmers globally.

Cellular Agriculture for Manufacturing Cultivated Protein

Cellular agriculture is an emerging novel technology with the aim of producing cultivated meat products, which is meat produced by growth of animal cells obtained via a biopsy, in a bioreactor containing growth media, that does not require the raising and slaughter of animals. This novel technology holds many proposed benefits for our food system, by reducing the burden of meat production on our environment, enhancing the nutritional content of meat, improving animal welfare, and boosting resource efficiency.

Cultivated meat has the ability to alleviate the strain of current large-scale meat production on all nine planetary boundaries, whilst still providing accurate nutritional content and taste of meat. For example, cultivated meat is estimated to reduce GHG emissions by up to 92%, due to the elimination of large-scale farming of methane-producing animals, with only a few animals required for providing cell biopsies. This reduction also alleviates strains on land use by an estimated 95%, by eliminating deforestation for livestock grazing and animal feed production, allowing for previously deforested land to be rewilded to restore biodiversity[36]. Further analysis of the benefits of cultivated meat on the environment and planetary boundaries was demonstrated in *Exhibit 1*.

Cultivated meat also reduces or eliminates the use of antibiotics, reducing the impact of meat production on antibiotic resistance and improving the safety of meat consumption. The nutritional content of cultivated meat can be controlled by altering the growth media components, for example to reduce the amount of fat, or increase the amounts of iron and B12. The texture of cultivated meat can also be more easily altered, for example to allow easier chewing for the elderly and children, providing an accessible source of protein and essential nutrients. However, there are currently many barriers to the adoption of cultivated meat, including high cost, technological limitations, regulation, and consumer acceptance.

[36] Good Food Institute, new studies show that cultivated meat offers massive climate benefits, 2021

In 2021, it was estimated that cultivated meat costs between $116- $22,423 per kg to be produced, with future costs estimated to be reduced to between $5.66- $17 per kg by 2030[37]. Current high costs are due to the small scale of cultivated meat production, and reliance on expensive media components, including Foetal Bovine Serum (FBS). Many companies are working on the development of affordable animal-free food grade growth media to facilitate the scale-up of cultivated meat technology. Despite current high costs and technological limitations, many countries are in favour of this emerging technology, with several countries already granting approval for sale.

Singapore became the world's first country to approve the sale of cultivated meat in December 2020, with the sale of cultivated chicken nuggets in the restaurant "Eat Just". Following Singapore's lead, several countries, including the US, have recently approved the sale of cultivated meat products, with brands including GOOD Meat and Upside Foods gearing up for market launch of their cultivated chicken products. Conversely, countries such as Italy have banned the sale of these novel food products to protect the livelihoods of their farmers. It remains uncertain whether the UK will join the list of approving countries, with many predicting they may do so by 2025, with companies such as Aleph Farms, Vital Meat, and Ivy Farms recently submitting for UK regulatory approval[38].

Cultivated meat must accurately mimic the biochemical composition of traditional meat, not just for safety and regulatory reasons, but also for consumer acceptance. If the taste and texture does not accurately resemble regular meat, consumers may be less likely to move towards this option. Alongside this, many consumers have limited information about cultivated meat and how it is produced, which may lead to further scepticism and neophobia. Therefore, transparency of companies is paramount to ensure consumer trust and acceptance. In a 2021 study with US and UK participants, 80% were open to trying cultivated meat, with 40% highly likely[39], showing that consumers are open to this novel technology, and many are willing to try it once it is approved and sold.

[37] Good Seed Ventures, Cultivated Meat Production Costs- Past, Present, and Future, 2021
[38] Cultivated Meat Startup Aleph Farms Files for UK Regulatory Approval, 2023
[39] Pub Med, US and UK consumer adoption of cultivated meat: a segmentation study, 2021

Proteins Derived from Plants, Algae, Fungus, and Insects

Many populations are shifting towards more plant-based diets, increasing demand for meat alternatives, due to environmental, nutritional, or ethical reasons. Currently 21% of the UK population identify as flexitarian, 12.5% as meat-free, and 39% reported reducing meat intake[40]. Consumption of plant-based products in the UK between 2008-2011 and 2017-2019 doubled, with an estimated more than 800 companies globally producing plant-based foods by 2020[41]. For example, Beyond Meat's Beyond Burger, made from pea protein, is available in approximately 130,000 stores and restaurants worldwide, in over 90 countries.

These plant-based meat alternatives are commonly made from soy, peas, beans, mushrooms, or wheat gluten, and can either be minimally processed, such as tempeh and tofu, or more heavily processed to mimic real meat with addition of many ingredients. The nutritional quality of these plant-based meat alternatives depends on these factors, especially when comparing to the composition of traditional meat. As well as plant-based, many meat alternatives have utilised fungi. For example, the company Quorn uses biomass fermentation of natural organism called *Fusarium Venenatum*. This fibrous fungus, also known as a mycoprotein, mimics the texture of meat, producing a range of popular meat alternative products. These products offer a widely accepted nutritious sustainable source of protein, that is low in saturated fat, high in protein, and a good source of fibre.

Algae, particularly strains chlorella and spirulina, are gaining traction as a new sustainable meat alternative, offering high protein content and low environmental footprint. Algae requires minimal water, no arable land, and contributes significantly to oxygen production. Recent studies conducted by the University of Exeter suggest algae successfully promotes muscle protein synthesis in humans, exemplifying its nutritional benefits for replacing meat products. Algae is versatile and is currently already used in many food ingredients such as agar, carrageenan, xanthan and guar gum. Several

[40] Novel plant-based meat alternatives: future opportunities and health considerations, 2023
[41] GFI, Plant-based Meat, Eggs, and Dairy, 2020 State of the Industry Report

companies are leading the way for the future production of algal meat alternatives, including Israeli startup Yemoja pioneering the development of red microalgae for plant-based burgers and steaks that mimic traditional meat. Algae also shows prospects for innovations in plant-based fish alternatives, with its unique flavours and high omega-3 content. For example, Philippines-based company "Worth the Health Foods" is currently working on frozen microalgae seafood alternatives.

Insects are currently being explored as another alternative protein source. Eating insects dates back thousands of years, and is commonplace in many countries particularly in Africa, parts of Asia, and South America. Insects account for up to 60% of dietary protein in rural African diets and form a large part of culture and cuisines in countries worldwide. For example, in Brazil, every October and November winged queen ants are collected and fried or dipped in chocolate as part of their traditions. In contrast, across Europe and the US, insects are not as accepted as a protein source, affected by neophobia, societal norms, misconceptions, and food safety concerns. However, currently there are many innovative companies across Europe developing insect-based foods. For example, French company Ynsect is leading the way in leveraging mealworms for creating insect-based ingredients applicable in food, feed, and fertilisers, showcasing innovative uses of insects across various industries. Horizon edible insects, based in London, is paving the way for the acceptance of insect-based foods within the UK, offering tours of their small-scale insect farm, insect cooking classes, and "grow your own mealworms" gift kits.

The EU has approved the sale of certain edible insects within the food market; however, the aftermath of Brexit has introduced complexities for the UK, necessitating the formulation of its own distinct regulatory framework for the approval of insects as food, with a temporary period of uncertainty[42]. The future of insect-based foods depends on both consumer acceptance and regulatory approval and represents a promising part of the future protein landscape. Utilisation of insects as food ingredients, including in the form of a protein-rich flour, could facilitate the shift towards insect-based foods, without the disgust or neophobia associated with the consumption of whole insects across Europe and within the US.

[42] Horizon Edible Insects, The Current Legal Status of Edible Insect in the UK, 2024

Digitalisation, Singularity, and the Internet of Thinking Things

Digital technologies comprised of Digital Twins, Artificial Intelligence, Robotics, Web 3.0, and the Metaverse, will by 2050 transform every sector, including the food system.

- **Digital twins** are comprehensive digital representations that precisely mirror real-world objects, systems, or processes, utilising data to simulate their physical counterparts in real time. They can be used in R&D, agriculture, manufacturing, distribution, healthcare, and consumer settings. By 2050, these technologies will become commonplace within the food supply chain, offering capabilities such as digital scenario simulation testing and real-time monitoring. It will become possible to create and connect digital twins of every object including equipment, machinery, factories, and even individual crops in a field. The connection of these digital twins will provide very powerful decision-making tools.
- **Artificial intelligence (AI)** is a field of computer science that creates systems capable of performing tasks that typically require human intelligence and cognitive thinking, such as visual perception, speech recognition, decision-making, and language translation. According to Ray Kurzweil, AI is predicted to achieve Artificial General Intelligence (AGI) capabilities before 2030, reaching the point of Singularity by 2045 and surpassing human cognitive intelligence with exponential acceleration of capabilities. This advancement will augment and simplify data analytics and the interpretation of digital twin models using AI interfaces and companions. AI neural networks and specialised ultra-fast AI chips will become ubiquitous, embedded within a vast array of both industrial and consumer products. This integration signifies a profound advancement in product intelligence, enabling enhanced functionality, efficiency, and user experiences across numerous sectors.
- **Satellites, robotics, and autonomous systems,** comprising of robots, co-bots, humanoid robotics, autonomous vehicles, drones, satellite systems, and autonomous production lines, will become commonplace across all sectors. These technologies, capable of operating 24 hours a day, will feature embedded sensors to capture data continuously. They will enhance productivity, sustainability, safety, and quality, marking a transformative shift towards more efficient and resilient food

production and distribution processes. RethinkX[43] highlights that: “Humanoid robots will enter the market at a cost-capability of under $10/hour for their labour, on a trajectory to under $1/hour before 2035 and under $0.10/hour before 2045”. To achieve $10/hour, it will require a humanoid robot that costs $200,000 with a lifetime of 20,000 hours before decommissioning. It is likely that the cost will drop to well below this value by 2050.

- **Web 3.0** represents the next generation of the internet, emphasising decentralisation, trust, transparency, and the empowerment of end-users, including the ability for consumers to own digital assets through blockchain technologies. This technology facilitates more user-centric services by enabling greater control over personal data and online interactions. Web 3.0 will also extend to the development of the Internet of Thinking Things (IoTT) by 2050. This will significantly advance the creation of a more interconnected and intelligent digital hive, comprising of AGI-enabled devices that can communicate and operate autonomously.
- **The Metaverse** is a virtual environment that combines enhanced digital and physical realities, where users interact with each other and computer-generated elements. This will be underpinned by Web 3.0 and augmented by Virtual Reality (VR), Augmented Reality (AR) technologies and AGI. It will provide a new channel for interactive user experiences within the food system across the entire supply chain, supporting industry and consumers through relevant multimedia content.

The digital revolution is poised to redefine the food system by 2050, transforming it into a network of interconnected digital twins that span from individual products and factories to entire supply chains and the wider sector and economy. Managed by various stakeholders, this network will harness vast amounts of data to drive unprecedented levels of traceability, transparency, productivity, and dynamic risk management throughout the food supply chain.

Challenges posed by the complexity of supply chains are being overcome through the emergence of Artificial General Intelligence (AGI). This will enable faster integration and interpretation of real-time data collected through smart sensors and intelligent robotic equipment across the supply chain and beyond. External data sources, such as weather forecasts, satellite data, relevant news alerts, and consumer trends, will be supplemented by detailed data from suppliers. This comprehensive data will culminate in a digital twin of the entire supply chain, securely accessible to all involved parties. Such collaboration will allow stakeholders to jointly simulate various supply chain scenarios, conduct risk assessments, evaluate sustainability efforts, and test new practices for their effectiveness and benefits. Web 3.0 technologies further secure this

[43] RethinkX: This time, we are the horses: the disruption of labour by humanoid robots, 2024

ecosystem, using blockchain to authenticate and protect data, thus ensuring data access and ownership integrity. The meticulous analysis facilitated by these digital innovations also enables the traceability of individual food items, creating a digital footprint that details the origin of the food and its production processes, including ethical, environmental, and safety standards. This level of detail empowers both companies and consumers to make informed decisions, backing the validation of ethical and sustainability claims, to foster a new era of trust and transparency.

Digital twins, enhanced by AI and Web 3.0 technologies, will markedly accelerate R&D, promote smart farming, automate production, minimise food wastage in transit, enhance supply chain adaptability, improve the traceability of food contamination, and empower consumers with the knowledge to make health-conscious and sustainable food choices. Notably, extensive data collection has facilitated precision agriculture practices for precise application of water and chemicals where required. Through the deployment of advanced digital tools, such as soil-scanning sensors, farmers are empowered to generate intricate field maps with real-time monitoring, enabling them to customise the application of crop protection products and fertilisers with unprecedented accuracy[44]. Digital twins are also set to simplify the implementation of carbon and nature accounting policies, which will utilise this supply chain data to understand the impacts on the planetary boundaries including freshwater use, biosphere integrity, land-use change, climate change, atmospheric aerosols, and biogeochemical flows. The analysis of this data will present the impacts of certain foods on our Earth's ecological ceiling, and thus the sustainability of the supply chain, and areas for potential improvement.

The advent of digital technologies is not only revolutionising the analysis of data across the supply chain but is also dramatically enhancing how consumers interact with and experience food. The burgeoning integration of the metaverse, Virtual Reality (VR), and Augmented Reality (AR) introduces a novel interface for both industry professionals and consumers. This innovation enables consumers to immerse themselves in digital representations of restaurants, engage in live cooking simulations, and partake in global food festivals, all from the comfort of their own homes[45]. Such advancements are reshaping the consumer food experience, integrating VR into physical dining spaces, and facilitating the e-commerce of tangible food items from virtual platforms. With the metaverse, the potential for consumer education, enriched food choices, and immersive experiences is boundless, marking a significant shift in the food industry landscape with numerous applications already making their mark.

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[44] World Economic Forum, What is Regenerative Agriculture? 2022
[45] FutureBridge, Metaverse in Food Industry, 2023

3D-Printing Will Enhance Customer Experience

3D printing, an additive manufacturing method, introduces innovative ways for consumers to experience familiar foods, including confectionaries, cakes, pasta, burgers, pizzas, and even steaks, through the use of digital software that accurately extrudes food-based materials into complex designs. This technology enables unprecedented customisation of food items in terms of their shape, size, and design, allowing for the creation of elaborate, tailor-made cakes and distinctive chocolate patterns. Small craft industries, particularly local cake artisans, will substantially benefit from this unique selling point, offering custom made cakes for special occasions, and with the potential for customers to claim ownership of their personal design through Web 3.0 platforms.

This customisability expands beyond aesthetic designs, with the ability to personalise textures and nutritional content. This can significantly benefit individuals with dietary restrictions or chewing difficulties, such as the elderly, by making foods more accessible and easier to consume but still appealing. For example, 3D printers are capable of employing lasers to meticulously cook food in layers during the printing process, enabling the preparation of ready-to-eat dishes like fish and meats with precision.

Furthermore, 3D printing is being explored for enhancing the nutritional value of foods. Current research is focused on producing chocolate that melts in the mouth but has a reduced fat content, by incorporating layers of the highest fat content on the exterior to maintain the desirable mouthfeel, with lower fat contents in the middle[46]. This technology promises significant benefits for individuals with specific allergies or medical conditions, allowing for greater control over ingredients, for example increasing fibre and reducing sugar content for diabetes patients. Additionally, 3D printing is under investigation for its potential to produce nutritionally optimised meals for space missions, where cooking and storage facilities are severely restricted, demonstrating its capacity to revolutionise how we prepare and consume food in various contexts.

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[46] BBC Food, Why 3D printed food is set to go mainstream, 2023

3D printing also presents opportunities for advancing environmental sustainability by repurposing food waste, such as vegetable skins, stale bread, and overripe fruit, into appealing new food products. A notable example is the Dutch startup Upprinting Food, which leverages this technology to convert such waste into uniquely designed baked crackers, showcasing an innovative blend of waste reduction and culinary art. Restaurants could leverage this technology in the future to turn in-house food waste into unique dishes, enhancing customer experience with personalised designs, reducing overall costs and waste, and promoting environmental sustainability.

One of the challenges with 3D printed food products will be the potential risk of using unhealthy substrates, containing additives and refined carbohydrates, to enhance the extrusion, deposition, and taste. As the technology evolves, these challenges may be tackled by the development of less processed substrates suitable for 3D printing, utilising food waste and everyday ingredients. The nutritional impacts of 3D printed products will vary largely, for example, a substrate made from nuts and seeds will be healthier than a substrate made from refined sugars and carbohydrates. Industrially produced 3D printed foods may contain more additives than those produced in home kitchens or by small artisan businesses.

Cultivated meat products can harness 3D printing technology to enable accurate replication of the texture of meat, through precise layer by layer production using different substrates. This occurs through the extrusion of scaffold materials containing animal cells from multiple nozzles, a process known as “Bioprinting”, which may revolutionise consumer acceptance of cultivated meat products through accurate replication of meat textures. Currently, cultivated meat products are largely limited to unstructured processed meats including burgers and nuggets, which are more easily produced within bioreactors. However, this evolving bioprinting technology could enable structured meat products to enter the market in the near future, including meat steaks and fish fillets. 3D printing technology can also be harnessed by the plant-based meat market, to enable customisability and a larger variety of products to be produced, that more accurately mimic real meat products.

3D printing is set to revolutionise both novel food production and the customisability of traditional food items. While the future popularity of 3D food printing remains to be seen, these devices could become commonplace in UK kitchens by 2050, contingent on affordability, the availability of ingredients, and user-friendly design customisation for those without programming skills. 3D printing aims to democratise the personalisation of food shapes, nutritional content, taste, and textures, for an exciting area of growth in home cooking and professional culinary arts, as well as its wider implications for the innovation of novel foods.

Regenerative agriculture focusses on the regeneration and protection of soils and their biodiversity to maintain farmland of high productivity and profitability, providing high quality food with reduced water and chemical inputs. Protection of our soils in the long-term is essential for the sustainability of large-scale farming, as within the next 50 years there may not be enough soil left to feed the world, according to Regeneration International[47]. Intensive farming contributes to the unsustainable release of GHG emissions, by disturbing the soils and relying on chemical fertilisers to maintain them, reducing long-term soil health. We must not only strive for short-term production of nutritious foods, but also for future generations, providing benefits to society today and in 2050.

By enhancing the natural ecosystems within the soils through regenerative practices, carbon sequestration within soils is facilitated, acting as a carbon store and contributing towards climate resilience and the restoration of our Earth System stability. Alongside this is the short-term benefits for farmers livelihoods and profitability, by enhancing crop quality and yields, and reducing inputs required. Regenerative practices also protect farmland from extreme weather events, such as flooding and droughts, which are becoming more frequent and intense due to climate change.

Regenerative agriculture is founded on six main principles, shown in *Exhibit 7*, that prioritise the conservation and protection of soils and biodiversity. These include reducing disturbance from heavy machinery and tilling, maintaining soil cover to prevent erosion, and enhancing plant diversity across the land. Livestock integration plays a supportive role, transforming plants into manure to enrich soil health and serving as natural grazers for cover crops. Regenerative farming excludes the use of chemical fertilisers and pesticides, protecting the soil's long-term health and preventing soil acidification. The recently added principle of holistic management is crucial, as the successful application of these principles relies on farmers' knowledge of their land's unique needs and conditions with a holistic view. Although regenerative agriculture

[47] World Economic Forum, What is Regenerative Agriculture? 2022

practices may vary between farms, the core ethos remains consistent: safeguarding soil integrity and promoting biodiversity.

Forum for the Future[48] highlighted in their 2023 report "Growing our Future" that regenerative farming could reduce UK agricultural GHG emissions by up to 38%, restoring soil health and ecosystems, and supporting farmer livelihoods. However, the incorporation of regenerative agriculture presents many hurdles for farmers, including its undefined parameters, the long-term nature of the transition, difficulties in tracking progress, and the risks tied to diversifying farm products and services. It is imperative for UK farmers to collaborate and share knowledge to effectively scale up new practices and tackle common challenges within the supply chain. Embracing regenerative agriculture principles is a process, not an immediate perfection; the ongoing effort and trajectory are crucial for cultivating a more sustainable agricultural system that ensures long-term soil health.

Strikingly, implementing these methods broadly has the potential to sequester over 10% of global carbon emissions within the soil over the next 25 years, drastically combatting the climate crisis and subsequently safeguarding the global food system. Through regenerative agriculture, farmers can address the increasing food demand while preserving soil vitality and productivity for future generations. This forward-looking approach enables agriculture and nature to coexist harmoniously, ensuring mutual benefits and fostering a sustainable, biodiverse soil ecosystem.

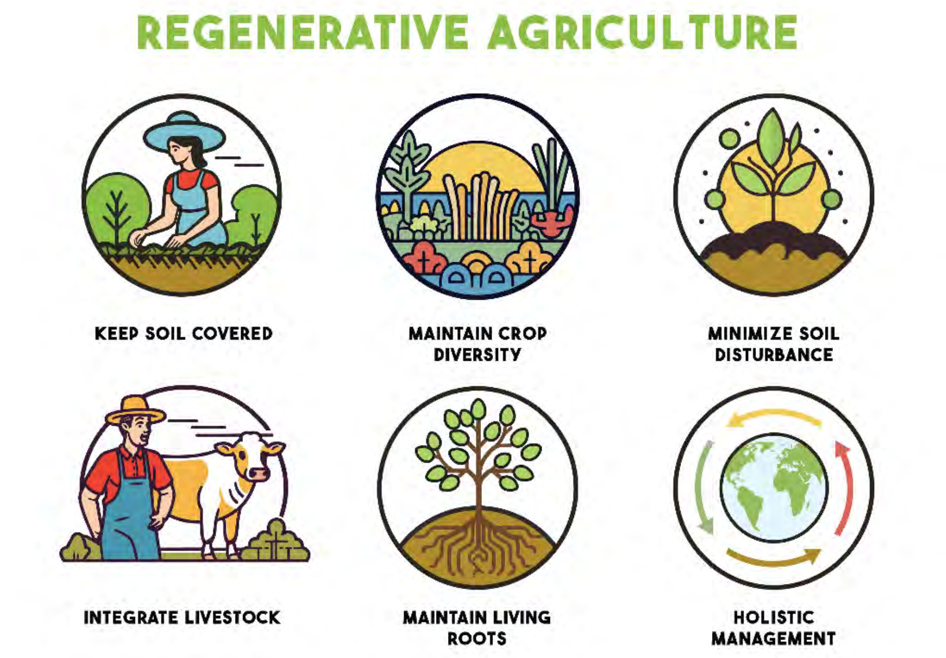

Exhibit 7: Six principles of regenerative farming

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[48] Working together to accelerate the transition to regenerative food and agriculture in the UK, Forum for the Future 2023

Vertical farming is another transformative farming practice, which brings farming indoors under controlled conditions, hidden from pests and promoting high efficiency of resource use in a small land area. Soil-less trays are stacked on top of each other, under artificial lighting and precise temperature, CO_2, and humidity control, and utilising robotics and data analytics for optimised and highly controlled production. The Internet of Thinking Things (IoTT) enables vertical farming to be monitored in real-time using sensors and image processing software, for precise tracking of growing conditions[49]. As climatic pressures worsen and weather pattens become more and more unpredictable, vertical farming offers a solution to protect crops from these external risks.

Vertical farming, including techniques such as aeroponics and hydroponics, offers up to 240 times the yield of traditional farming while utilising 98% less water and 99% less land[50]. Despite these benefits, high energy demand has been a significant limitation, now being addressed with energy-efficient LED lighting in targeted red and blue spectra, drastically cutting energy consumption. The integration of renewable power sources, such as solar panels, has further diminished the energy footprint of these operations. Embracing circularity, vertical farms not only minimise energy-use, but also resource use and waste streams, implementing circular materials and practices including rainwater harvesting and closed-loop water recycling. Furthermore, vertical farming eliminates the use of chemical pesticides and herbicides, providing benefits to public health, and eliminating the environmental degradation and water contamination usually generated by traditional farming runoffs. This constantly evolving technology can continue to enhance these variables for an efficient system with limited negative impacts on the environment, for large-scale reliable and minimally impactful food production.

Vertical farming, which uses minimal land area, will be particularly essential in supplying foods to urban areas, where 68% of our global population is expected to live by 2050[51].

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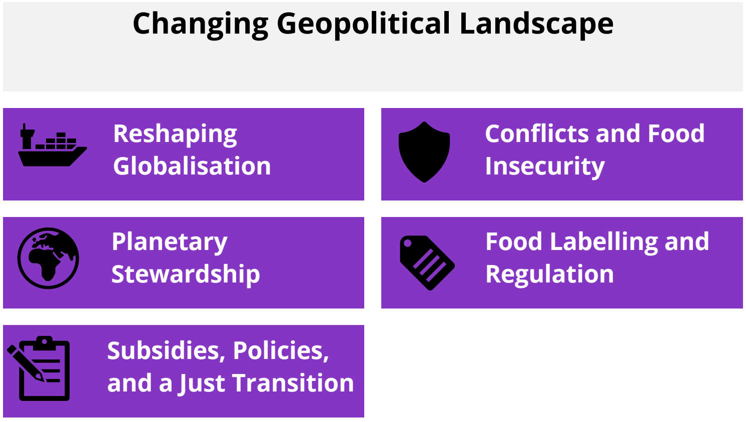
[49] Vertical Farming Planet, Vertical Farming Technology: How Does it Work? 2024
[50] World Economic Forum, How vertical farming can save water and support food security, 2023
[51] 68% of the world population projected to live in urban areas by 2050, United Nations 2018

Urban vertical farms will serve as vital sources of fresh safe foods all year round for the local community, especially in highly dense regions and food deserts, and where productive nearby cropland is insufficient to meet the needs of the urban population. Although vertical farms currently require a large upfront cost and are mainly limited to production of leafy greens and salads, this technology is constantly evolving. By 2050, vertical farms will likely be able to produce a large variety of healthy fresh foods to our global population, acting as a substantial part of our future food system. The incorporation of emerging digital technologies will allow for even more control over optimisation of conditions and producing a larger variety of fruits and vegetables, such as strawberries. For example, the UK's most advanced vertical farm located in Gloucestershire[52], consisting of 15 floors, plans to radically change the UK's dependency on foods from other countries, by eliminating imports of soft fruits, herbs, and salads to the UK within a decade. Although this is an optimistic target, it is reachable with technological advancements and optimised operations using smart monitoring, AI, and digital twins.

[52] Gloucestershire vertical farm is one of UK's 'most advanced', BBC news 2024

Geopolitical forces are reshaping food supply chains and we anticipate the emergence of an international governance body for planetary stewardship.

Changing Geopolitical Landscape



Summary

- Globalisation will persist, but will evolve in response to rising political tensions, with more agile localised supply chains that foster both self-reliance and reliance on trade between allied nations.
- By 2050, the establishment of a dedicated intergovernmental Commission for planetary stewardship is anticipated, that will utilise a real-time digital twin of the Earth System to help maintain the industrial complex within the planet's ecological ceiling.
- Entities such as the Earth Commission, World Business Council for Sustainable Development (WBCSD), Science-based Targets Network (SBTN), and Taskforce for Nature-related Financial Disclosures (TNFD) are paving the way for this future, establishing collaborative protocols for businesses to account and report their impact on the Earth System.
- The Paris Agreement, signed in 2015, emphasises the need for a "Just Transition" where no one is left behind, including future generations. This must be considered when shifting subsidies for facilitating introduction of novel technologies, whilst protecting farmers livelihoods and future populations.
- The transition to the future food system will lead to a massive shift in the current agricultural system, likely facing resistance from many affected stakeholders, whilst creating opportunities for new technologies and innovative business models.
- Hunger fuels conflict and conflict fuels hunger, with 74 million of the 110 million people enduring accurate hunger in 21 countries affected by conflict and insecurity, highlighting the necessity for conflict mitigation within the "Just Transition".
- Food labelling regulations, including introduction of mandatory environmental labelling, and nomenclature of novel foods, influence consumer choices and thus acceptance.
- Regulatory processes are essential for testing the safety of novel foods, to ensure public health is protected. This must be balanced with the facilitation of regulatory approvals for the incorporation of new sustainable foods to the markets.

Food production operates as an intricate global industry, characterised by complex supply chains that extend across all nations. In the next twenty years the sector will undergo significant transformations, reshaped by several forces including geopolitical tensions and drivers. Whilst **globalisation will persist, its nature will evolve**, markedly influencing both the food production system and the broader economy. This evolution will lead to the strengthening of supply chains among western allied nations, as these nation states strive to reduce their reliance on resources from countries where political and economic ties are under strain, notably Russia and China. Such shifts are indicative of a strategic realignment towards more resilient and dependable regional supply networks, aiming to mitigate vulnerabilities and enhance food security on a global scale.

This changing landscape underscores the necessity for these adaptive strategies in the governance of food production supply chains, ensuring they can navigate the complexities of international relations, emerging global challenges, and potential conflicts. As such, the food production supply chains must be agile, more localised, prepared to respond to shifts in geopolitical dynamics, and innovative in fostering cooperative relationships across nations, thereby securing a stable and efficient system. For example, escalating risks across global shipping routes, caused by global tensions, are leading to longer shipping times and costs. Consequently, the UK must look to more domestic foods to reduce reliance on these vulnerable container ships and improve self-sufficiency. Movement towards a more localised food system would allow the UK to focus on the development of domestic novel foods and alternative proteins, paving the way for a climate resilient future food system with less emphasis on globalised supply chains.

As we navigate towards this more resilient future food system, it is imperative that our policies and regulations are meticulously crafted to not only safeguard our people and nations, but also the Earth System we all depend upon, to enhance overall planetary health. **This holistic approach aims to foster planetary stewardship** and integrate whole systems thinking into the production and consumption of food. By 2050, the establishment of a dedicated commission or governing body is anticipated, one equipped with the expertise and tools necessary to monitor and analyse the impact of food supply chains on all nine planetary boundaries. This entity will be pivotal in devising and enforcing policies and strategies that effectively protect both the environment and humanity from adverse impacts, potentially utilising a digital twin of the Earth System containing vast amounts of real-time and environmental data for simulating scenarios.

The groundwork for such a visionary future is already being laid through **various taskforces and bodies**, including the Earth Commission, World Business Council for Sustainable Development (WBCSD), the former Taskforce for Climate-related Financial

Disclosures (TCFD) and the recently formed Taskforce for Nature-related Financial Disclosures (TNFD). TCFD and TNFD taskforces are driving transparency and accountability by urging companies to comprehensively report their climate, nature, and broader planetary impacts. The disclosure protocols developed from TCFD and TNFD are being tested and deployed through the Science Based Targets Network (SBTN), which offers a framework for companies to establish and pursue scientifically validated emissions reduction and nature positive targets. Through these collaborative and forward-thinking efforts, we are establishing a toolkit for Carbon and Nature Accounting, to measure the impact of industrial activity on the planet. This is protecting nature by appreciating its value to society and the economy, enabling the development of a sustainable and resilient system for future generations.

By aligning corporate strategies with scientifically grounded targets, businesses can ensure their operations contribute meaningfully to the global efforts encapsulated by the Paris Agreement and to reach net zero targets for 2050. The Paris Agreement's ambitious target of limiting global warming to 1.5°C above pre-industrial levels, which is currently off-track, highlights the urgent necessity for a systemic overhaul, notably within the food system which accounts for one-third of global greenhouse gas emissions. Within the Paris Agreement, the term “just transition” has been spotlighted as an essential part of transformative climate action.

The concept of a "Just Transition" within the Paris Agreement emphasises the necessity of a future that benefits all people, workers, and communities. Historical evidence has consistently highlighted the importance of justice, inclusivity, and transparency as central pillars of any transformative agenda. Without careful management, the shift towards a climate-resilient future risks amplifying social inequalities, deepening social divides, and marginalising minority groups, which could lead to civil unrest. The ethos of a just transition is to ensure that no one is left behind, thereby smoothing the path forward as reduced resistance and fewer socio-economic disruptions lead to more cohesive and contented populations. Ensuring the food system experiences a “just transition” and navigating its geopolitical landscape will be challenging in many aspects, and the food system’s shift is likely to face growing resistance from the affected agricultural stakeholders, including farmers. Fast-paced changes in regulation, subsidies and technological advancements, the rise of competitive novel products, and fluctuating demand pose threats to the current food and agricultural industries.

In the aftermath of World War II, subsidies were introduced to the food system to bolster food security and stabilise farmers’ incomes, primarily supporting intensive farming and cultivation of the “big four” crops of corn, rice, soybeans and wheat. However, these traditional subsidies have increasingly led to environmental degradation and the creation of an uneven playing field for smaller farmers. Many regions have started to recognise these issues, notably the EU with its Green Initiative, a pioneering subsidy reform allocating 30% of funds to sustainable farming practices, including “rewilding” to maintain biodiversity and natural landscapes. Although these subsidies were well intentioned, these reforms have sparked widespread farmer protests, marches, and demonstrations. Farmers feel these legislations are threatening their livelihoods amidst other challenges such as global competition, trade disruptions, inflation, and the cost-of-living crisis. This opposition and resistance is likely to continue as we transition within this complex food landscape, and there is no easy way of facilitating this shift.

Farmers also feel increasingly threatened by the emergence of competitive novel foods, including plant-based proteins, cultivated meat, and fermentation-enabled products. For example, alternative dairy brand “Perfect Day” provides low-cost animal-free nutritionally equivalent milk alternatives to the market, that may eventually out-compete dairy. Farming representative from ProVeg highlighted that “Plant milk is made in a factory, not on a farm. Most of the value chain moves from the farmers to the industry. Farmers fear becoming irrelevant, losing their livelihoods.” This showcases the main concern of farmers today of being left behind, within a rapidly evolving food system moving towards novel alternatives[53].

The competitiveness and success of these new technologies is largely limited by current subsidies for traditional agricultural farming practices, which must be taken into consideration when transitioning to the future food system. Governments are thus tasked with a delicate balancing act: enabling climate and nature-positive farming practices and introduction of novel foods to the market, whilst also ensuring the transition is inclusive, protecting the livelihoods of those within the farming community. Despite the hurdles, the transition offers farmers the opportunity to reshape their practices to provide new ingredients and even manufacture onsite alternative milk and protein food products for retailers and consumers, boosting their profitability. To remain competitive, farmers must adapt their business models effectively alongside government legislative changes. This will enable them to integrate into the future food system that utilises emerging technologies and novel processes, which will still require a vast array of farming inputs.

A “just transition” must also take into consideration the alarming **interplay between conflict, political unrest, and hunger**, and aim to alleviate the self-sustaining cycle of poverty. The United Nations World Food Programme (WFP) starkly highlights that "Hunger fuels conflict, and conflict fuels hunger." This reinforcing relationship underscores the critical importance of food availability as a cornerstone of peace. The Global Network Against Food Crises (GNAFC) 2021 report highlights that conflict stands

[53] Harvesting the future – opportunities for farmers in alternative proteins, ProVeg 2024

as the principal catalyst for food insecurity and hunger, pushing nearly 100 million people into acute food insecurity, a significant increase from 77 million in 2019. Such crises spotlight the necessity for a food system transformation that integrates climate action with conflict mitigation strategies. According to the Food and Agriculture Organisation (FAO), an overwhelming majority of those facing chronic food insecurity, 490 million out of 800 million, reside in countries affected by conflict. Furthermore, the WFP highlights that 74 million of the 110 million people enduring acute hunger are in 21 countries marred by conflict and insecurity. This vicious cycle is threatened to be further reinforced by escalating climate change impacts, extreme weather events, and shifting food growing conditions, that undermine food security and can spark conflicts over land, food, and resources. Tackling this issue during the “just transition” is critical, for minimising risks of further conflict and food insecurity worldwide. The Lancet 2021 report highlights that addressing this challenge requires a multifaceted approach, targeting the production and distribution of sufficient food, meeting the nutritional needs of populations, ensuring equitable benefits, and minimising the environmental footprint, to forge an equitable food system for all.

Food labelling regulations play a crucial role in the ongoing transformation of the food system, serving as a vital tool for consumers to gauge the quality and safety of their food choices. The essence of effective labelling lies in its clarity, honesty, and simplicity, ensuring that consumers are not misled by complex or deceptive information. While current regulations mandate the inclusion of nutritional details and allergen warnings, they fall short in requiring disclosures about a product's environmental footprint. The oat milk company Oatly is spearheading efforts to mandate climate labelling, arguing for the necessity of transparent, accessible information on the ecological impact of food products, through their innovative campaigns challenging the dairy industry to provide their climate footprint figures. Mandatory environmental labelling would empower consumers to make decisions that align with their values, directly influencing the sustainability of their diets. However, this information must be as accurate as possible to ensure that consumers can trust any eco-claims made and compare products effectively.

Beyond nutritional information and climate impacts, labelling will also play a role in the acceptance and regulation of novel foods entering the market during the food system transformation, for example cultivated meat. The debate over appropriate labelling for such products, whether it be called "lab-grown meat," "cultured meat," or "animal-free meat", highlights the challenge of communicating clearly to consumers without causing confusion or misleading them. Establishing a consensus on nomenclature is essential for ensuring that the labelling of these novel foods is understandable nationwide, thereby supporting an informed and transparent transition.

Regulation not only plays a role in food labelling, but also in the acceptance of novel foods to the market. Although some view regulatory processes as barriers to the innovation of novel foods, these measures are essential to ensure that new products meet rigorous safety standards and offer sufficient nutritional value for mass consumption. Stakeholders pioneering the development of innovative foods must navigate the regulatory landscape with precision, optimising ingredients and gathering comprehensive data to streamline the approval process. Achieving a balance between the rapid deployment of these innovations and the imperative to safeguard consumer health is pivotal. Regulation is an essential part of the transformation of the food system, and regulatory procedures must evolve alongside new technologies to facilitate the acceptance of new environmentally friendly food innovations to the market. For example, currently the sale of cultivated meat has been approved in only two countries, Singapore and the US, but many countries are expected to join the list over the next few years, including the UK, Switzerland, Australia and New Zealand. This showcases the lengthy approval timeframe of novel foods but suggests that there will be a momentum build as more nations witness successful approval and sale.

The future food production-consumption system must operate within the Earth's ecological ceiling by 2050, providing healthy, nutritious, and affordable food to over nine billion people.

Foresighting the Future Food System

This section depicts the probable features of the future food system in 2050, providing a prediction of the most likely scenarios across the sector from farm to fork.

Part II: Foresighting the Future Food System

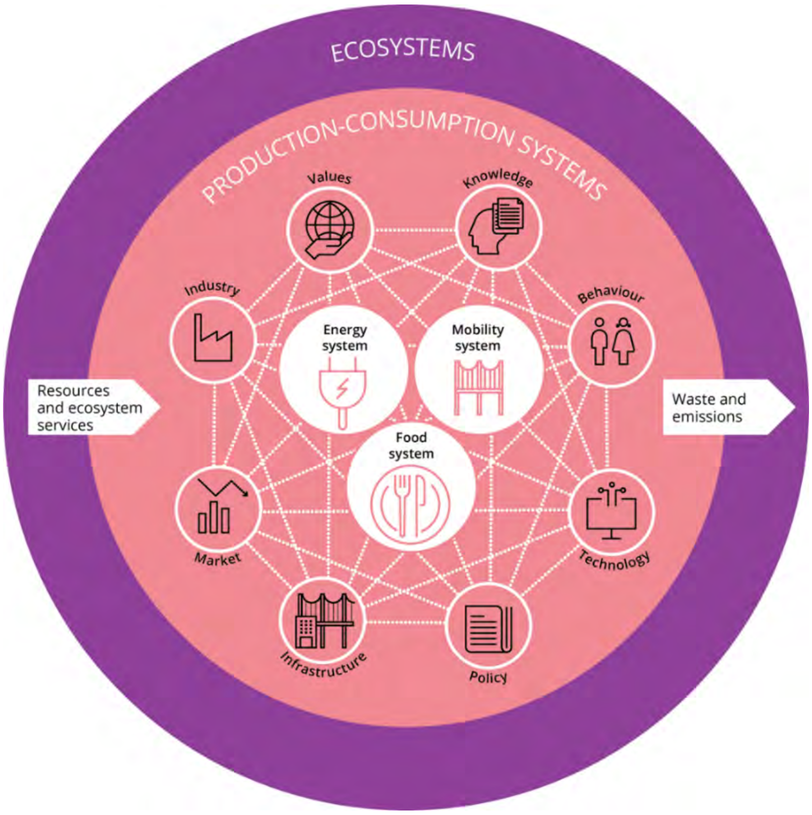


Exhibit 8: Future production-consumption system
Image credit: European Environment Agency

By 2050, technological advancements will go far beyond what we can conceive and imagine today, accelerated by the emergence of **artificial general intelligence (AGI)**. This progress will enable AI platforms to perform a wide range of cognitive activities at human-like levels. Ray Kurzweil, Futurist, has predicted that human society will reach **technological singularity** around 2045, where a form of Artificial Superintelligence (ASI) will drive what are today unforeseeable technological advancements. Foresighting society and industry in 2050 hence requires us to account for the availability of at least Artificial General Intelligence (AGI), which will drive rapid discoveries and technological advancements across various domains. It will disrupt business as usual and result in the development of autonomous farms, factories, and services, spanning all sectors.

By 2050, we will be firmly within the **Anthropocene epoch,** where industrial activities are the dominant force influencing the Earth System and its stability. Our industrial complex, as shown in *Exhibit 8*, must be operating within the Earth's **ecological ceiling**, protecting the stability of the Earth System and hence its ability to support human life. The environmental context will be very much dependent on the extent to which climate change has progressed by 2050. Global average temperature rise will have exceeded 1.5°C before or near 2030. The global community faces the challenge of slowing down these rising temperatures and deploying carbon-negative solutions, ensuring that by 2100 global temperatures have been successfully reduced back to below 1.5°C. From an industrial perspective, this will require the development of Nature Positive supply chains. If little progress is made in addressing climate change, we could face a scenario where global average temperatures rise near or above 2°C, or even 3°C, by 2100. The scale of the challenges faced by future generations will be enormous, with unprecedented environmental risks and significant costs to human life, the economy, access to food, and global security. For example, the intensifying severity of extreme weather events is likely to significantly increase the costs of insuring trade, logistics, buildings, and other assets, potentially rendering insurance prohibitively expensive or even unattainable for many. Furthermore, the risk of fatal extreme "wet-bulb" heatwave events will rise, placing the lives of people in many poor communities at risk in locations such as South Asia, the Middle East, and parts of Africa. These regions are particularly vulnerable due to their already high baseline temperatures and humidity levels.

By 2050, industry must reconfigure supply chains and the wider industrial complex to operate within the Earth's ecological ceiling. Simultaneously, it will need to provide products and services to consumers whilst ensuring the **social foundations** and broader needs of over nine billion people are met. This comprehensive approach must align with the Sustainable Development Goals, to promote sustainability and global well-being. With respect to nutrition, the current food system poses significant risks due to ultra-processed foods, which negatively impact lifespan, healthy aging, quality of life, and healthcare expenditures. These foods contribute to chronic diseases like cardiovascular disease and diabetes, necessitating innovation, research, and a shift in industry towards producing less processed, more micro-nutrient-dense foods.

These huge challenges represent huge opportunities. The transformed technological, environmental, and societal landscape will result in a very different business culture to the one industry has been accustomed to, alongside new social norms, behaviours, lifestyles, and consumer expectations. This will open the door for new production methods and business models. Over the coming decades, forward-thinking stakeholders will collaborate towards a successful transformation of the industrial complex, adopting a holistic whole-systems approach. A shared vision, known as "**Vision 2050: Time to Transform**" has been developed by industry and recently published by the World Business Council for Sustainable Development. By 2050, governments will unlikely be using Gross Domestic Product (GDP) alone as an indicator of economic performance, but rather on a set of parameters that measure the wider value of economic activities to society and the environment. This evolution in economic measurement will promote the emergence of inclusive growth and prosperity, potentially grounded in frameworks such as Kate Raworth's Doughnut Economics Model. Such frameworks emphasise sustainable development that balances societal needs with environmental limits. This is also an approach that Amsterdam City, West Midlands Combined Authority and many other regions are exploring and adopting in varying forms to shape their economic and urban development strategies.

To achieve this, the industrial complex will integrate **regenerative and circular economy principles** into new products and supply chains by 2050, having undergone a fundamental shift in mindset. This shift will be from a linear degenerative economy of production, use, and waste, to a sustainable **nature-positive closed-loop model** that emphasises reuse, repair, recycling, repurposing, remanufacturing, durability, and modular designs as well as restoring nature to strengthen the Earth's climate resiliency. This approach benefits the environment and society by minimising impacts of resource extraction and waste streams, and more importantly alleviating the pressure on all nine planetary boundaries[54]. Furthermore, the circular economy supports sustainable long-term economic prosperity, and promotes national internal economic growth.

The environmental crises may lead to the formation of a **Planetary Stewardship Commission**. Such a body would be charged with the mission of maintaining the Earth System within the ecological thresholds of a Holocene-like state. With advances in digital technology, a real-time digital twin of the Earth System could be developed and made accessible to all. This digital twin could gather data from an extensive network of sensors and satellite imagery, monitoring variables such as changes in land systems and the impacts of global supply chains on the Earth's ecology. Powered by AGI, it could feature a user-friendly interface that aids in identifying trends and patterns, uncovering issues, and monitoring the planet's health. Such technology would enhance decision-making capabilities and foster planetary stewardship. It would also be accessible to consumers and companies, allowing businesses to collect real-time environmental data about their supply chains, and for disclosure to consumers.

In all sectors, including the food system, AGI will be harnessed for the deployment of interconnected humanoid robots, capable of tracking and autonomously undertaking tasks alongside humans. It will give rise to the **Internet of Thinking Things**, comprising of smart connected objects with embedded AI systems. This will boost the productivity of production systems, including farms, and will lead to the creation of more high-tech skilled jobs. As these systems evolve, they will unlock a realm of new possibilities providing huge opportunities for those who harness the power of AGI, driving rapid advancements and reshaping our world in currently unforeseeable ways. However, this could create huge risks of inequality for many regions and communities worldwide, if not managed effectively by governments and stakeholders. AGI and autonomous farms, factories, deliveries, and services would require fewer human operators.

[54] Circularity Gap Report 2023, Deloitte and Circle Economy Foundation

As shown in the table below transformation of the food system will be significant as it moves to operate within the Earth's ecological ceiling and harnesses advancements in technology:

2050 Food System	Key Features
Production of Sustainable Fertiliser	• Synthetic fertilisers are vital for food security; however, they account for over 2% of global GHG emissions. Their over-use has broken the Biochemical Nutrient Flow planetary boundary and is threatening the Stratospheric Ozone Depletion boundary. By 2050, fertilises production and use will need to be far more sustainable to ensure Nature Positive supply chains. • Anticipated advancements in fertiliser production include the use of sustainable hydrogen for manufacturing nitrogen-based fertilisers via Haber-Bosch. Additionally producing bio-based closed-loop fertilisers from organic waste, formulating nano-fertilisers and microbe-based fertilisers, and deploying onsite electrochemical cells for the synthesis of green ammonia.
Sustainable Use of Pesticides	• Insect populations are declining, exemplified by the UK's flying insect population diminishing by 60% over the past two decades, which poses a threat to food security and biodiversity. This is a result of the unintended impacts of agriculture practices, such as the overuse use of pesticides. • By 2050 it will be crucial to significantly reduce the use of pesticides, eliminate their use where possible, and deploy more sustainable alternatives. These include the use of biological control organisms, light-based, biochemical, enzyme-enabled, mineral-based, microbial-based, nanotechnology-based and RNAi pesticides. These will be deployed using precision technologies, alongside integrated pest management approaches.
Smart Regenerative Crop Farming and Orchards	• By 2050 farmers will have integrated regenerative nature-positive closed loop farming practices, such as polyculture, to boost sustainability, biodiversity, soil health, water filtration and to sustain future yields. Many small farmers will have established community forest gardens, designed around permaculture. • Low-cost "plug and play" AGI-enabled cloud platforms will be available offering digital twins and IoTT capabilities to connect equipment, robotic machinery, drones, and humanoid robots across the farm. • Drones and robotic machinery will utilise imaging technology to develop a digital twin of the farm, establishing the health and condition of individual plants. This will aid the deployment of Integrated Pest Management (IPM), regenerative farming practices, and precision technologies that target fertilisers and weed-killing lasers.

Smart Indoor and Vertical Farming

- By 2050 cities, towns and communities globally will adopt smart indoor growing for access to fresh, flavourful, nutritious, and sustainable produce at affordable prices all year-round. This will help to eliminate "food deserts", strengthen local food security and reduce costs of fresh produce. Indoor Farms could expand to fruits and vegetables, and even staple crops by or beyond 2050.
- Indoor and vertical farming will be highly efficient, harnessing specialist connected equipment, lighting, robotic equipment, AGI platforms, and IoTT capabilities operating 24/7, regardless of the season and time of year.
- Indoor growing capabilities could extend to home kitchen units providing optimal growing conditions, allowing individuals with no garden space or those within food deserts to have easy access to fresh salads and other produce.

Shift to Alternative Proteins

- Global palates will shift towards less processed plant-based proteins, including tofu, tempeh, beans, and pulses, but with many still harbouring a preference for meat.
- Technological advancements and regulatory approval will provide many novel proteins to the market, such as insect flours, algae, and fungi, with varying levels of consumer acceptance.
- Disruption of the dairy and meat industries by 2050 will begin with the incorporation of low-cost, nutritional, and environmentally sustainable precision-fermented dairy proteins into food products. This transformation will extend to whole dairy products, including milk, yoghurt and cheese.
- This will accelerate the rise of cellular agriculture, including unstructured and eventually structured meat products, becoming more affordable than factory-farmed meat well before 2050. This will allow the repurposing of land previously used for livestock.

Smart Regenerative Livestock Farming

- According to WWF, agriculture accounts for 80% of global deforestation, occupying 38% of the world's land including half of the world's habitable land.
- By 2050, intensive factory farming operations will no longer be an economically viable way of supplying the bulk of our protein. It will be disrupted by cultivated meat and alternative proteins in response to the escalating climate crisis and biodiversity crisis.
- Many medium- to small-scale farms will remain in 2050, harnessing regenerative practices, smart technologies, and methane reduction techniques. These farms will produce niche premium meat products, as well as supplying cultivated meat producers with cell biopsies.
- Robotic livestock herders in the form of "robotic dogs" and drones will be deployed for livestock herding and monitoring.

Sustainable Aquaculture and Fisheries

- The scale of wild fishing will drastically decline by 2050. Remaining wild fishing will be highly regulated and monitored in real-time using intelligent tracking systems alongside drones and subversive robotic vessels, to protect threatened fish stocks.
- By 2050, fish consumption will remain a prominent protein source globally, and sustainable land-based and freshwater aquaculture farms will provide the bulk of our seafood. Alternative fish feeds are essential to make aquaculture truly sustainable, including fungi-based, insect-based and algae-based options already being researched.
- Remaining marine-based fish farms will adopt smart technologies to scan and monitor the health of individual fish, to detect sea lice and segregate diseased fish for treatment with antibiotics. This will reduce fish losses to improve the sustainability of these practices.
- By 2050 omega-3 rich plant-based alternatives, algae-based alternatives, and cultivated fish products will be available, developed alongside alternative meat products, providing low impact alternatives to consumers.

Smart Food Processing, Factories and Packaging

- The 2050 food manufacturers will produce less ultra-processed foods, driven by rising consumer awareness, and government regulation due to rising costs of healthcare. Technologies including 3D printing will be utilised to improve nutritional content of foods whilst maintaining mouthfeel and taste.
- Autonomous smart factories will be widely used and highly efficient, integrating robotic machinery, AGI capabilities, IoTT, metaverse technology, and interconnected humanoid robotics, with limited need for human intervention.
- Real-time digital twins of food items will drive manufacturers to reconfigure supply chains to become nature positive, including sustainable farms and suppliers. This shift will involve the adoption of sustainable alternative packaging materials.
- Consumers will have increasing access to supply chain data, facilitating transparency of the sustainability of individual foods.

Food Distribution, Services and Consumption

- The ways foods are chosen, delivered, prepared, and consumed will be transformed by 2050 by the rise of longevity foods, AR supermarket glasses, VR online supermarkets, drone deliveries, robotic and autonomous kitchens, and robotic servers.
- Restaurants will offer fully immersive experiences, harnessing augmented reality and flexible screens for consumer engagement and customisability.
- Home kitchens will be equipped with novel appliances such as 3D printers, indoor growing units, and mini cultivated meat bioreactors for at-home production of fresh foods.

Production of Sustainable Fertilisers

The resiliency of food supply in the UK and most nations is deeply dependent upon access to fertiliser. By 2050, the manufacturing of fertilisers will be profoundly influenced by the adoption of new technologies, environmental policies, and the imperative need for agriculture to be Nature Positive and operating well within the Earth's ecological ceiling. Several key methods will dominate the landscape of fertiliser production, each contributing to a more sustainable and efficient agricultural sector.

Here are five of the anticipated production technologies:

1) **Geological, Purple and Green Hydrogen-Based Ammonia Fertiliser Production:** One of the most promising developments in fertiliser production is the use of geological, purple, and green hydrogen. Generated through the electrolysis of water powered by nuclear or renewable energy sources, purple and green hydrogen respectively represent a low carbon alternative to hydrogen derived from natural gas. Recent discoveries have found geological hydrogen locked deep in the Earth, which could be extracted and harnessed in the future. All three will form viable sources of sustainable hydrogen in 2050, to be used as feedstocks for the Haber-Bosch process. During this process sustainable hydrogen reacts with nitrogen from the air to produce ammonia, without the carbon emissions typically associated with traditional methods. This ammonia can then be converted into various nitrogen-based fertilisers, such as urea and ammonium nitrate. In 2050, the production process for sustainable ammonia will be via renewable and nuclear energy. One likely method will be a scalable array of micro-nuclear reactors that can co-generate purple hydrogen and power Haber-Bosch and other processes along the value chain. The adoption of sustainable ammonia reduces the environmental footprint of fertiliser production and serves as a sustainable fuel for shipping and other applications, becoming a key energy vector in the hydrogen supply chain.

2) **Production of Bio-based Closed-Loop Fertilisers:** By 2050, advancements in biotechnology are expected to significantly enhance the production of bio-based fertilisers. This will utilise anaerobic digestion processes and organic materials, such as compost, animal manure, and various organic waste products including food waste and sewage sludge. These bio-fertilisers will not only repurpose waste, but also promote environmental sustainability by improving the soil's structure and increasing its organic content. Further, the development of engineered bio-solids

and microbial inoculants will improve nutrient availability and plant uptake. These innovations include beneficial microbes that can fix atmospheric nitrogen or increase phosphorus solubility, reducing the need for synthetic fertilisers. This approach will not only recycle valuable organic materials but also support the soil's microbiome, enhancing its health and fertility. By 2050, such nutrient recovery will become a standard practice, driven by technology that allows for efficient extraction and conversion of these nutrients into usable forms.

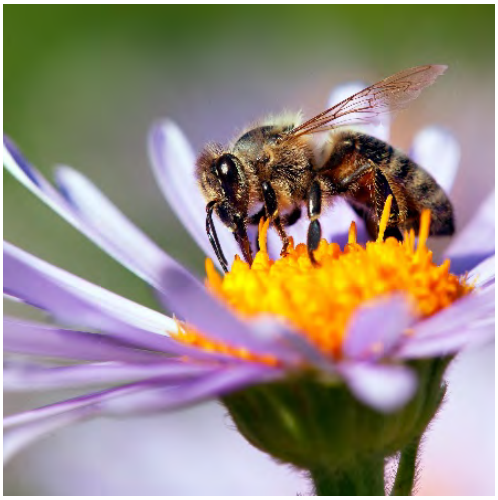
3) **Production of Nano-fertilisers for Precision Agriculture:** The use of nanotechnology in fertiliser production for precision farming will have arrived by 2050 and will be widely used by farmers. Nano-fertilisers will be designed and formulated to deliver nutrients more efficiently to plants, ensuring they are released in a controlled manner. This reduces losses due to leaching or runoff that adversely impact the biochemical flows of phosphorus and nitrogen into rivers, streams, lakes, and oceans. Nano-fertilisers will not only minimise environmental damage but will also enhance nutrient-use efficiency and crop yields. Nano-fertilisers can also improve soil structure by promoting aggregation and water-holding capacity and enhancing microbial activities. Coupled with precision agriculture techniques, nano-fertilisers in 2050 will be applied in a more targeted manner, ensuring that nutrients are provided at the right time and in the right amounts, tailored to the needs of specific crops and soil conditions.
4) **Microbial-based Fertilisers:** By 2050, advancements in microbiology and biotechnology will enable the manufacturing of nutrients for plants. Scientists and industry leaders will have perfected methods to synthesise nutrients using genetically modified bacteria and other microorganisms. These engineered organisms will be capable of fixing atmospheric nitrogen or solubilising phosphorus from natural sources, offering a sustainable alternative to traditional chemical fertilisers produced via the Haber-Bosch process. This innovative biomanufacturing approach will not only reduce the reliance on energy-intensive production methods, but will also decrease dependence on non-renewable mined resources, such as phosphate rock.

5) **Electrochemical Synthesis of Green Ammonia.** The electrochemical production of green ammonia has the potential to become an innovative reality by 2050. This approach employs electricity generated from renewable sources such as solar and wind to generate ammonia, without the associated carbon dioxide emissions of traditional methods. The production process starts with the electrolysis of water into green hydrogen and oxygen using renewable energy, whilst simultaneously nitrogen is extracted from the air. These elements are then introduced into an electrochemical cell where, facilitated by a catalyst, nitrogen reacts with hydrogen ions under the influence of an electric current to form ammonia. This production

process, whilst slower, operates under far milder conditions than the traditional Haber-Bosch process. Whilst its adoption in large-scale facilities for fertilisers will be challenging due to the slow chemical reaction, it holds promise for deployment by 2050 as small electrochemical cells utilised onsite in facilities such as indoor and vertical farms. A network of electrochemical cells can be connected directly to water and nutrient flow systems to generate low-cost green ammonia onsite.

By 2050, the combination of these innovative methods will transform how fertilisers are manufactured, leading to more sustainable and efficient agricultural practices. They will be utilised in crop fields, as well as indoor and vertical farming facilities. The integration of sustainable hydrogen, bio-based technologies, nutrient recycling, and nanotechnology into the food system will address environmental challenges of traditional fertiliser production and support a growing global population sustainably. A critical focus of fertiliser management will be in preventing overuse, to mitigate the runoff of phosphorus and nitrogen, effectively controlling bio-geochemical flows into aquatic systems. This strategic approach will safeguard freshwater ecosystems, reducing the adverse impacts on biodiversity in waterways. Comprehensive regulations and precise application techniques will be essential in maintaining ecological balance and protecting aquatic life.

Sustainable Use of Pesticides



The huge decline of insect populations is a wake-up call for the agricultural industry. Insects are fundamental to global food security, fulfilling critical roles in pollination, decomposition, and natural pest control. They are essential pollinators of various crops, ensuring the production of fruits, vegetables, and nuts. Additionally, insects like earthworms contribute to soil health by decomposing organic matter and recycling nutrients, thus maintaining agricultural fertility. Moreover, certain insects serve as natural predators of pests, reducing the need for chemical pesticides. Insects are essential for pollination, supporting approximately 75% of the world's flowering plants and 35% of global agricultural lands. The decline of insect populations, exemplified by the UK's flying insect population diminishing by 60% in the past two decades, poses a significant threat to food security, ecosystem stability, and biodiversity.

Pesticides, whilst crucial for pest control of certain insects, weeds, and fungi, can have widespread and unintended consequences on insects and wildlife. They disrupt ecosystems, affecting biodiversity, soil health, and ecosystem services. Pesticides can harm non-targeted organisms, leading to biodiversity loss and disruption of natural food chains. The elimination of natural predators of pests can upset predator-prey relationships, exacerbating pest problems. Pesticide residues persist in the environment, contaminating soil, water, and vegetation, posing risks to wildlife through direct exposure or ingestion. Pesticides can disrupt the soil microbiome, reducing microbial diversity and activity, which over time diminishes soil fertility and agricultural productivity. This disruption undermines the crucial ecological functions that maintain long-term soil health and crop yields. Secondary poisoning occurs when predators and scavengers consume contaminated prey. This phenomenon affects various species, including birds, mammals, and humans, further disrupting ecosystem dynamics.

By 2050, government regulations are likely to evolve to include testing new pesticides for their effects on the human gut microbiome. It is now known that certain pesticides impact the gut microbiome, which plays a crucial role in regulating the digestive system, immune function, and overall health and wellbeing. Indeed, there have been several court cases related to the adverse effects of pesticides on human health. As our understanding of the gut microbiome deepens and testing technologies advance, these new regulations will aim to enhance safety standards and promote population health by ensuring that pesticides do not adversely affect this vital aspect of human physiology, including mental health.

By 2050 indoor farming settings will help to reduces overall pesticide use in the wider food system by cultivating crops in controlled environments like vertical farms and greenhouses. These settings are far less vulnerable to pests, allowing for integrated pest management strategies that prioritise biological and physical controls over chemical pesticides. Advanced technologies such as hydroponics and climate control systems create optimal conditions that discourage pest infestations. Additionally, automated monitoring systems and physical barriers further minimise pest threats, ensuring healthier produce and promoting environmental sustainability by eliminating chemical runoff and preserving ecosystems.

By 2050, the sustainable use of pesticides in outdoor agricultural settings will be crucial for minimising impacts to the environment whilst ensuring effective pest control. Integrated pest management (IPM) approaches, which combine various pest control methods, including biological, cultural, and chemical controls, will become increasingly important. IPM is an environmentally sensitive approach to pest control that combines various practices to manage pest populations effectively and sustainably. It involves accurate identification of pests and regular monitoring to make informed decisions about control measures. Preventative cultural practices, such as crop rotation, sanitation, and the use of pest-resistant crop varieties, are fundamental to IPM, affected by the behaviours and values of certain farmers in different regions. Biological control methods promote the use of natural enemies like predators and pathogens to manage pests. Mechanical and physical controls, including traps, barriers, and poly-cropping, also play a crucial role, reducing the ability of pests to reach the crops. Chemical control is used judiciously as a last resort, selecting targeted and low-toxicity pesticides to minimise harm to humans, non-target organisms, and the environment. Evaluation of the effectiveness of these measures is essential to ensure long-term success and adaptability. IPM aims to reduce reliance on chemical pesticides, lower costs, protect human health, and promote sustainable pest management strategies that adapt to changing conditions and pest behaviours.

By 2050, robotic machinery will reduce pesticide use by adoption of precision agriculture for implementing IPM approaches. The use of robotic machinery for applying targeted pesticides will significantly reduce human exposure, particularly for farm workers and local communities. The high levels of precision offered will reduce overall pesticide usage and minimise off-target effects. Adopting a range of diverse pesticide options and enhancing ecological balance by conserving the natural predators of pests are crucial steps towards nurturing healthier ecosystems and securing long-term food sustainability for the future. Looking ahead to 2050, advancements in technology and a growing awareness of environmental sustainability are reshaping the landscape of pesticides.

The types of pesticides that are anticipated to be predominant in agricultural practices by 2050 are shown in the table below. The combination used will be dependent upon specific settings and needs of the crop, environmental surroundings, regional regulations, and the farmer's value proposition to the target consumers.

Type	Description	Examples
Biological Control Organisms	• Utilising beneficial insects, microbes, and other organisms, these biological agents naturally manage pest populations without synthetic pesticides.	• Ladybugs actively consume aphids, controlling their population naturally.
Light, Electricity and Mechanical Methods	• Utilise specific wavelengths of light or lasers to control pest populations, minimising chemical use and environmental impact. • Mechanical weeding methods	• Electric sparks and laser systems targeted to selectively kill weeds. • Infrared light can be used to raise the temperature of pests to lethal levels in grain silos.
Chemical Attractants or Repellents	• Chemicals that lure insects into traps or controlled areas, and chemicals that deter insects.	• Pheromone traps for insects, and citronella oil for repelling insects.
Biochemical and Enzyme-based Pesticides	• Consist of naturally occurring substances or botanicals that control pests through non-toxic mechanisms such as disrupting mating or feeding behaviours.	• Azadirachtin, derived from neem seeds, disrupts hormonal systems of pests. • Proteases that degrade the protein structures in insect exoskeletons, causing damage.
Mineral-Based Pesticides	• Derived from natural minerals, often used in organic farming	• Sulphur and copper-based compounds.
Microbial Pesticides	• Utilise microorganisms such as bacteria, fungi, viruses, or protozoa to target specific pests.	• *Bacillus thuringiensis* bacteria produce toxins lethal to certain insect larvae.
Nano-Pesticides	• Employing nanoparticles to improve delivery and effectiveness of pesticides, reducing the amount needed and the environmental impact.	• Nanoparticles encapsulate pesticides to enhance penetration through insect cuticles, increasing efficacy.
RNA interference (RNAi)-based Pesticides	• Utilise RNAi technology to target and silence genes crucial for pest survival, without affecting other organisms.	• RNAi sprays target specific pests like Colorado potato beetles by disrupting vital genetic processes.
Gene-Editing Pesticides	• Crops are genetically engineered to be pest-resistant or to produce their own pesticidal substances.	• CRISPR-Cas9 technology used to enhance the natural defences of plants against pests.

Precision and Regenerative Farming for Crops and Orchards

By 2050, the impacts of climate change and the need for a more resilient food system will have significantly transformed crop farming and orchards, underpinned by the IoTT.

Regenerative practices to address the environmental crisis will have become widespread for crop farming and orchards to help maintain soil health. As climate change worsens, rising global temperatures will cause heat stress on temperature-sensitive crops like wheat, maize, potatoes, and rice, reducing yields. Additionally, altered precipitation patterns will lead to droughts and floods, each adversely affecting crop growth. In the UK, for example, wheat yields dropped by 40% in 2020[55] due to a combination of heavy rainfall and droughts. Climate change will increase the occurrence and persistence of bacteria, viruses, parasites, harmful algae, fungi and their vectors in crops, orchards, and livestock farming. Furthermore, shifts in growing seasons and patterns will disrupt plant reproductive cycles, reducing yields and impacting food supply chains and prices. The extent of the progression of climate change will determine which global regions will lose their historical crop and orchard farming capacities.

To mitigate these climate risks by 2050, the agricultural sector must have adopted an array of resilience strategies. For example, developing drought and heat-resistant crop varieties using advancements in selective breeding and gene editing, and enhancing water and soil management strategies. Many farmers will have moved from monoculture to polyculture operations, with many smaller farmers also adopting community forest gardens based on permaculture practices. These adaptations are crucial for maintaining agricultural productivity in the face of climate change and ensuring food security. Thus, tackling the challenges posed by climate change on agriculture requires global cooperation, innovative research, and robust support for farmers.

By 2050, the UK will need to enhance its self-reliance in food production to ensure and improve food security. Onsite autonomous **anaerobic digestion facilities** will help close the loop by converting organic waste into biogas and biofuels. Combined with onsite wind and solar, it will help to supply renewable power to both the farm operations and to nearby communities. The byproduct, a nutrient-rich digestate, will

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[55] Impact of climate change and biodiversity loss on food security, House of Commons, 2022

serve as an organic fertiliser, enabling a closed-loop system within farming practices and reducing synthetic fertiliser use.

The Internet of Thinking Things (IoTT) will reshape every aspect of crop farming and orchard management from soil preparation and seed sowing to water irrigation, fertilisation, pest control, disease prevention, harvesting, and post-harvest handling of produce. At the core of this transformation will be Artificial General Intelligence (AGI) and the shift to regenerative nature positive closed-loop practices.

By 2050, both small independent and large-scale farming operations will have low-cost access to **"plug and play**" cloud-based platforms provisioning digital twin and AGI system capabilities. The platform will be able to easily integrate data from diverse sources, including weather forecasts, satellite data and images, robotic machinery, drones, energy systems, inventory planning systems, and sensors. The AGI platform will evolve and maintain a comprehensive real-time digital twin of the farm's operation, crop fields, orchards, and indoor facilities down to the individual plant. A field for example could readily be scanned using imaging technology by a hive of drones or autonomous tractors, scanning individual plants and fruits for their health and readiness for harvesting, to build a digital twin of the field.

A digital twin of the field or farm will function as an extensive management tool, simulating real-world operations and allowing for pre-emptive strategy adjustments to optimise yield. It will enable the establishment of the environmental footprint of the farm's operations, highlighting impacts on the Earth's planetary boundaries and gathering carbon and nature accounting data. Leveraging satellite technology will provide unparalleled insights into weather patterns, emissions data of gases such as methane and nitrous oxide, land conditions and even pollution levels in nearby streams, rivers, and lakes. Integrated with a powerful AGI Companion, the platform will deliver real-time analysis and recommendations to aid farmers in optimising farm operations. Such insights will help refine various agricultural practices, including refining planting and harvesting schedules, as well as optimising the precision use and application of fertiliser and pesticides.

By mid-century, it is anticipated that low-cost humanoid robots, autonomous farming machinery, robotic tractors, and drones will be deeply integrated into farming systems. These technologies will handle tasks from seeding to harvesting, with humanoid robots performing complex activities such as moving objects and operating certain equipment. Drones will be crucial for continuous crop monitoring and environmental management, using advanced imaging to assess the health of individual plants, and precision capabilities for targeted fertilising, weeding, and harvesting individual fruits at optimal times. As such systems evolve, farming will transition to full autonomy, reducing human intervention, and enabling a non-stop operation.

Smart Indoor and Vertical Farming

As we enter 2050, indoor and vertical farming will have already become mainstream, propelled by the convergence of advanced technologies including robotics, automation, AGI, IoTT, and renewable energy. This will be harnessed within a closed loop system utilising LED lighting, water recycling systems, and smart sensors for optimal growing conditions and minimised resource use. Farming indoors will provide communities with fresh, flavourful, and nutritious produce at affordable prices all year round, including a vast array of salads, fruits, vegetables, herbs and spices, and potentially even staple crops.

Indoor and vertical farms of 2050 will operate continuously 24/7, 365 days a year, with minimal need for human intervention. These sophisticated systems will heavily utilise advanced robots and autonomous systems designed to deliver precise amounts of nutrients and other inputs for optimal plant growth. Central to their efficiency and cost effectiveness by 2050 will be the IoTT, which will dramatically transform the ways we gather, analyse, and respond to agricultural data. IoTT technologies will utilise a smart network of sensors and devices that continuously collect and transmit data on crop health, environmental conditions, and resource use to sophisticated AGI systems. These AGI systems will analyse patterns of individual plant growth, adjusting variables such as humidity, light intensity, and nutrient levels in real-time.

Alongside this, advanced humanoid robotics and autonomous machines will carry out physical tasks ranging from precise planting of seeds to the delicate harvesting of ripe produce, all enabled by information delivered from the AGI systems. These robots will monitor crop health through advanced imaging, detecting sights of disease before they become visible to the human eye. By automating these processes and utilising predictive analytics, indoor and vertical farms will not only maximise yield and quality of produce, but also minimise waste and resource consumption, alleviating the environmental impacts of farming. These advanced technologies will, by 2050, enable the UK to domestically grow complex fruits and vegetables indoors that are usually imported from abroad, such as cantaloupes, aubergines, and avocados[56]. Importantly, by 2050, grains and staple crops could become economically viable for growth in indoor and vertical farms, utilising genetic modifications that yield shorter, more nutrient-

[56] Vertical Farming Planet, What Can Be Grown in Vertical Farms? 2024

dense, and faster growing crops that can be grown in vertical trays. This viability will be bolstered by the incorporation of renewable energy, lower costs of electricity, and advancements in robotics and AGI. The successful implementation of staple crops in vertical farms, although challenging, would provide massive benefits to the sustainability of global food production, substantially reducing global freshwater usage.

Indoor and vertical farming will significantly reduce the burden of food production on all nine **planetary boundaries**, using only a small fraction of the land and water that traditional farming demands. In these highly controlled environments, the need for herbicides and pesticides will be eliminated, and fertilisers will be used minimally and only where necessary. This will lead to a significant decrease in environmental pollution and a reduction in food contamination risks for consumers. Additionally, these conditions will protect crops against disease outbreaks that often plague outdoor farming, ensuring more consistent and reliable food production. Simultaneously, by 2050, vast areas of land previously cleared for conventional agriculture will have been rewilded and restored, fostering thriving biodiversity and revitalising ecosystems worldwide. The operational footprint of indoor and vertical farms will be minimised by optimisation of energy use, such as employing specific wavelengths of LED lights for maximised plant growth, alongside adoption of 100% renewable and sustainable energy, easily incorporated by 2050. Moreover, circular systems, such as collection and recycling of rainwater, will further diminish the resource demands of vertical farms, reducing environmental burdens and lowering operational costs.

Indoor and vertical farming will also provide benefits to society, in terms of nutrition, access, and the palatability of foods. Foods will be grown in conditions optimised for enhanced taste and nutrition, rather than for prolonged shelf life and stability during long distance shipping, due to being grown locally and readily distributed. Some vertical farms will be located in small factories within densely populated cities and food deserts, some will be in largely arid regions burdened by droughts, and others will be found 100 feet underground[57]. Although outdoor farming will remain essential for plants and crops unviable for indoor growing, these vertical farms will provide populations with large amounts of essential fresh produce. This will reduce reliance on imports from other nations, eliminate restrictions of growing seasons, and enhance overall access to foods in regions that once could not grow certain foods. Although this is a potential threat to local cuisines, this provides populations with an expansive selection of healthy foods, of which they can choose to incorporate into their everyday diets. Vertical farms will also aid communities in times of crisis, for example vertical farms were able to successfully adapt production to meet

[57] Forward Fooding, Vertical Farming: the Key to Sustainably Feeding 9 Billion People by 2050?

demand surges during the Covid-19 pandemic, due to shorter growing times than conventional farms[58].

Beyond large-scale food production, indoor farming capabilities could even extend to **kitchen devices and units**, that can be harnessed by individuals to grow produce at home over a few weeks, in a clean environment. This would alleviate pressures on our large-scale food system and improve access to healthy foods, by allowing consumers to grow foods in a small space in their kitchens, rather than needing access to a garden or allotment. This would be particularly useful in densely populated urban areas which can struggle to access fresh produce, and sometimes rely heavily on overly processed and tinned foods. These kitchen units would also be used by restaurants and retail outlets, facilitating access to fresh produce grown in-house. The possibilities of vertical farming are endless and will be utilised alongside outdoor farming practices to provide the global population of 2050 with a sustainable and reliable source of nutritious foods.

[58] Financial Times, Coronavirus crisis fuels interest in vertical farming, 2020

Shift to Alternative Proteins

Production of traditional meat, fish and dairy as we once knew it will have rapidly declined, due to the drastic and massively visible pressures of climate change and biodiversity loss on our planet, making it an unsustainable way of producing the bulk of protein sources within western countries by 2050. Thus, meat, fish and dairy produced by traditional methods will no longer continue to be the dominating protein products within society, and by 2050 will remain only as niche products sold at a premium price. As a result, by 2050, we will have shifted towards an array of alternative proteins competing against one another for consumer demand. This alternative protein market will be made up of cultivated meats and fish, precision fermented dairy products, fungi and algae, insect-based products, whole legumes and pulses, and plant-based meat mimics with varying levels of processing.

By 2050, the western population's palates will shift towards less processed sources of plant-based proteins, including tofu, tempeh, beans, and pulses, that aim to benefit the gut microbiome and promote human health. Importantly, by 2050, preferences for these minimally processed products will become the norm, as successive generations gradually move beyond the need for mimicking real meat. Western populations will rely on less processed plant-based foods for a large majority of their protein sources, with a large variety of options. This drastic shift, that will change consumer behaviour and palates, will be fundamentally catalysed by the driving force of the climate crisis on society and industries. Although many will move towards these plant-based proteins, a significant number will continue to harbour a preference for meat consumption in 2050.

Alongside the plant-based movement will be the introduction of novel protein sources, **including insects, algae, and fungi**, which will contribute towards the 2050 alternative protein market. Supermarket products will incorporate ingredients sourced from insects, and many bakeries will opt for high-protein, insect-based flours over traditional wheat for their breads and cakes. While whole insects might not gain widespread popularity in Western countries by 2050, or provide the bulk of meat substitutes, they will be seamlessly integrated as indistinguishable ingredients in everyday food products, offering nutritional benefits without altering familiar textures and flavours. As for algae, this will propel as a substantial alternative to meat and fish products, with many cultures opting for this omega-3 rich source of protein, with its unique umami taste. However, algae will be most widely utilised in the fish feed sector, for feeding of carnivorous fish within sustainably managed aquaculture farms.

By 2050 fungi meat alternatives, including mushrooms and mycelium, will have greatly expanded in variety offering products that closely replicate the distinct tastes and textures of traditional meats, and utilising precision and biomass fermentation methods. This diversification will have been enabled by the approval and integration of a broad range of fungal species into the food system, allowing these products to mimic a vast array of meat products. The fungi-based meat market will be characterised by a broad spectrum of companies, each leveraging a diversity of fungal species and unique bioreactor technologies to offer distinctive products. Among these, particular production methods will rise as the most successful, becoming the preferred choice for restaurants and retail outlets due to its consumer appeal.

By 2050, the disruption of the dairy and meat industries by precision fermentation "food farms" will be well-established, with these compact production facilities becoming commonplace. These farms will efficiently produce dairy and meat products on a small land area, offering affordable, healthy proteins for a wide range of food products that previously depended on one of the most inefficient systems: the cow. As the RethinkX report predicts, this shift will have begun with the business-to-business integration of precision-fermented proteins like whey and casein into food products including protein bars and shakes rather than relying on shifting consumer choices. This disruption will extend to beloved dairy products such as cheese, milk, yoghurts, and ice cream, which will be inexplicitly the same or even better in nutrition, taste and textures of products that used to originate from a cow.

This rapid decline in the viability of the traditional dairy sector will have led to the acceleration of the adoption of these technologies for production of meat within bioreactors, initially of minced meats and unstructured products. This will, by 2035, extend to enabling of the viability and advancements of cellular agriculture and cultivated meats[59]. These will be cost effective and widely consumed well before 2050, ultimately rendering the traditional cow-based industry unviable, leading to its decline with only some remaining livestock farms. The once-dominant role of the cow alongside other animals in our food system will be overtaken by these sustainable innovative alternatives, marking a significant turning point in how we produce real meat and dairy.

Although plant-based alternatives will be widely consumed by the public in 2050, a substantial segment of the population will continue to harbour a **preference for real meat**, influenced by cultural traditions, heritage, and consumer palates. Widespread meat consumption will be enabled through the use of cultivated meat technologies, accelerated by the disruption of the dairy and meat industries. This technology will be expanded to a large-scale by advancements in AI and bioreactor design, with cultivated meat making up the bulk of affordable real meat products within supermarkets,

[59] Rethinking Food and Agriculture 2020-2030, RethinkX 2019

restaurants and other retail outlets. Furthermore, by 2050, the acceptance and expansion of novel foods will be enhanced and validated by biological ageing tests. These tests will effectively assess the long-term health implications and safety of new products, thereby boosting societal acceptance and further validation of cultivated meats.

Cultivated meat will significantly alleviate the pressures on all nine planetary boundaries, as shown in *Exhibit 1*, enabling large-scale meat production to continue into 2050 in a sustainable way. For example, cultivated meat eliminates the large-scale farming of methane-producing livestock, drastically reducing GHG emissions from the food system which currently contributes to over ¼ of global emissions. Alongside this, cultivated meat is predicted to alleviate freshwater usage of meat production by up to 96% and reduced freshwater contamination from runoffs. This is due to the elimination of large-scale livestock farming and irrigation for feed production, promoting food security in regions of increasing water scarcity. In all aspects, cultivated meat can reduce the negative impacts of meat production on our planetary boundaries and Earth System stability.

Although cultivated meat will contribute significantly to environmental stability, it poses **considerable challenges to various industries** that depend on the cow's other valuable assets. This includes the use of cattle hair, skin, fat, and bones, for the production of a wide array of materials, chemicals, and products sold worldwide. This includes everyday products such as detergents, medicines, vitamins, leather goods, shampoos, adhesives, inks/dyes, and even paint brushes. However, by 2050, these byproducts will have been successfully replaced by alternative materials, including those derived from precision fermentation such as cultivated leather. Precision fermentation will be universally employed to produce specific materials and ingredients affordably and sustainably, effectively addressing the needs of these industries, whilst reducing reliance on traditional animal sources.

Smart Regenerative Livestock Farming

By 2050, large-scale intensive factory farming of cattle, chickens, pigs, and other livestock will no longer be needed to supply the bulk of our protein, with cultivated meat and precision fermented dairy available at an affordable price, and many opting for plant-based and other alternative proteins. As a result of this drastic reduction in livestock farming, large swathes of land will be rewilded allowing previously farmed lands to restore their biodiversity and act as a carbon sink. Livestock farming will likely continue on a medium- to small- scale within bespoke farms still producing traditional meats, and others raising the animals to provide cells for cultivated meat production. This approach will involve many farms harnessing regenerative farming practices that integrate livestock with crop farming, with others utilising advanced methane-reducing techniques to alleviate emissions from the remaining animals, especially cattle. In this new farming landscape, livestock will be recognised as valuable assets to own and raise with higher levels of animal welfare and greater freedom to graze.

By 2050, current livestock factory farming on such a large and intensive scale, which currently provides the UK with 70% and the US with 99% of its meat[60], will no longer be economically viable. This will occur due to the rising success of precision fermented dairy and the viable production of cultivated meat, with many factory farms being replaced with high-tech production facilities for novel meat and dairy products. This will require livestock farmers to shift their economic models to integrate into this new system, for example raising livestock for contribution to cell biopsies in cultivated meat, production of crops for ingredients and feedstocks of novel foods or managing rewilded areas. Some will adapt to become regenerative farms, and others will alter their factory farming procedures to be more sustainable. Transitioning to this 2050 vision will present considerable challenges, including resistance from stakeholders and difficulties faced by traditional farmers in adapting to new policies, farming practices, and technologies. However, the ultimate outcome will be a highly productive and sustainable food system. This transformation is expected to generate a large amount of high-tech innovation jobs within the agricultural sector, fostering the growth of new food companies and technology businesses, thereby revitalising the industry after its period of transition.

[60] Our World in Data, How many animals are factory-farmed? 2023

This shift away from intensive livestock farming will free up vast areas of agricultural land previously used for animal grazing and factory farms, paving the way for global rewilding and reforestation efforts. These initiatives will revitalise damaged soils and restore the integrity of the Earth's biosphere. The return and recovery of biodiversity within natural ecosystems will not only protect threatened species but will also enhance the environment's resilience and ability to buffer climate change by functioning as natural carbon sinks. Fewer livestock and subsequently lower feed production will also result in lower levels of pollution from agricultural runoffs into freshwater systems. This will result in a reduction in eutrophication and harmful algal blooms that threaten marine life and the livelihoods and health of communities. Ultimately, the transformation we will see by 2050 will foster a sustainable co-existence between agricultural systems and the natural world, creating a more balanced global ecosystem.

Although meat production from intensive livestock farming will significantly plummet by 2050, various **medium- and small- scale farms will remain** producing bespoke traditional meat products for local communities and niche exports. To remain economically viable and become environmentally sustainable these farms must have adapted by 2050 to improve productivity and reduce their overall impacts on the planet. Many of these farms will incorporate regenerative farming practices integrating livestock with crops to nurture the soils with manure production. This type of farming aims to maintain soil fertility and allow food production to remain balanced with nature, without damaging the farmland in the long-term. These small-scale regenerative farms will be largely smart farms, harnessing advanced AGI, IoTT, drones, sensors and robotics. For example, individual animals can be closely monitored through thermal imaging to detect their health and wellbeing, and drones and robots can act as "sheepdogs" to herd livestock such as cattle and sheep[61].

Competing with regenerative farming may be some remaining factory farms, that will aim to harness methane-reducing techniques to reduce the environmental impact of their livestock. This will be facilitated by advancements in selective breeding, alternative cattle diets, supplementation of diets, reduced use of antibiotics, and the development of effective anti-methane vaccines. We may also find certain hybrid-farms combining regenerative farming approaches with methane-reduction techniques, with both grass-fed and grain-fed cattle. The 2050 blend of regenerative farms, factory farms, cultivated meat, and alternative proteins within the market will be shaped by the extent of the climate crisis, government regulation, and the purchasing choices of consumers. Ultimately, we anticipate that cultivated meat and alternative proteins will become the dominating protein sources, with a small number of regenerative and factory farms present in 2050.

[61] National Geographic, The future of livestock farming, 2019

By 2050, selective breeding techniques will have been harnessed over the previous years to breed lower methane producing cows, facilitated by genetic testing and analysis of the heritability of this trait. This will contribute towards the reduction of methane emissions from entire herds by reducing the large variations between individual animals on the same diet and in the same environment.

Methane production will be further reduced by altering the feed of these cows. Much evidence suggests that cows on diets higher in fats and grains can release 80% less methane than grass-fed cows. The unique selling point of grass-fed cows is the nutritional profile, with high levels of omega-3 content. Thus, the reduction in methane emissions from feeding these cows with more grains would diminish the USP of the meat produced for its target consumers. This would create competition between grass-fed and grain-fed meat on the market, each presenting a different value proposition to consumers and benefits to the environment. The incorporation of grains to grass-fed cows' diets within a hybrid farm model aiming to reduce methane emissions would compromise the purpose of that product.

Although grain-fed cows produce less methane than grass-fed, this does not take into **consideration the emissions from the whole system** including synthetic fertiliser use in the production of grain feeds, and the transportation of this feed to livestock farms. Producing more localised supply chains and incorporating regenerative farming practices into crop production would reduce the GHG emissions from grain-fed cattle farming overall. Furthermore, by 2050 there may be an introduction of various novel animal feeds acting to alleviate land areas required for traditional feed production, for example utilising precision fermentation for protein production harnessing carbon capture from waste industrial gases.

Farmers can further reduce methane emissions of grain-fed cattle by **supplementing their diet** with molecules that inhibit the action of methane-producing enzymes in the animals' stomach, without posing any threats to the animal's welfare or health. For instance, the addition of organic component 3-NOP to cattle feed can inhibit enzymes involved in methanogenesis, potentially reducing methane produced by cows by 30-90%. Similarly, Asparagopsis, a seaweed which contains the compound bromoform, has been shown to block enzymatic reactions that produce methane[62]. Notably, seaweed cultivation does not require land, freshwater, or fertilisers, making it an environmentally sustainable option that can be used to substantially cut cattle methane emissions. By 2050, researchers are expected to identify the most cost-effective, safe, readily available, nutritional, and environmentally friendly supplements for reducing methane

[62] The Guardian, Kowbucha, seaweed, vaccines: the race to reduce cows' methane emissions, 2021

emissions. As well as methanogenesis inhibitors and seaweeds, these supplements could include essential oils, organic acids, probiotics, and antimicrobials.

By 2050, advancements in methane reduction could extend beyond dietary interventions. Scientists may have successfully developed **safe and effective methane-inhibiting vaccines** for cattle, engineered to produce specific antibodies in the saliva that migrate to the rumen and disrupt methanogen formation. This innovation would enable farmers to more effectively reduce emissions from both grain-fed and grass-fed livestock, offering a simpler alternative to dietary supplements. However, this approach introduces a new dilemma as to whether consumers opting for grass-fed traditional meat products would accept meat that has been vaccinated, and whether this would affect the nutritional quality of the meat.

Overall, the future of livestock farming will be largely shaped by a **substantial reduction in numbers** and with remaining livestock farms adapting to become more sustainable. Beyond food production, livestock will continue to hold significance within religion and culture with livestock featuring in many religious festivals and viewed as symbols of wealth and status. For example, during the Pongal Hindu Festival in India, livestock are celebrated as symbols of wealth and sustenance, often featuring cows adorned with colourful garlands. In 2050, these types of events will remain with livestock continuing to play an important role in many communities worldwide.

Sustainable Aquaculture and Fisheries

Growing demand for seafood has placed increasing pressures on wild fish populations and marine biodiversity. By 2050, sustainable aquaculture farms found on land-based facilities and integrated into freshwater systems such as lakes and floodplains will provide the majority of fish stocks to the global population, some of which optimising land area through vertical stacking. Some wild fishing will remain, but with the elimination of large-scale intensive overfishing and harmful trawling procedures. Any wild fishing will need to be sustainable and will be monitored in real-time using robotic equipment to ensure sustainability. Remaining marine aquaculture farms will harness advanced digital technologies including AGI, machine learning, and sensors, to monitor individual fish health, for example iFarm. Alongside this will be many plant-based fish alternatives and cultivated fish products that will supplement aquaculture farms to fill global demand, but on a much smaller-scale than cultivated meat. Fish will provide billions of people with a low impact sustainable and nutritious source of protein and omega-3 fats in 2050, whilst we collectively ensure the protection of marine life and recovery of oceanic health. Alternative fish feeds will allow aquaculture to become truly sustainable, by not relying on the capture of wild fish stocks for feeding carnivorous fish such as salmon. Fisheries will remain an integral part of many communities worldwide who rely on fish farming for their livelihoods and culture.

The scale of wild fishing will drastically decline by 2050. The future of fish production will involve a diverse mixture of practices working in unison to maintain a balance between maintaining oceanic ecosystems and meeting the global demand for seafood. Importantly, this will involve a drastic reduction in large-scale wild fishing, with the elimination of the use of massive nets and trawlers that harm marine life and deplete fish stocks faster than they can replenish themselves. This alleviation will allow many threatened species to recover and for the biodiversity of our ocean to begin to thrive again. That being said, many local communities that rely on fishing for their livelihoods and income will continue to fish at a small scale within global protocols, with many valuing the taste and tradition of consuming wild caught fish. Protecting fish species against illegal wild fishing and overfishing practices will likely remain a challenge in 2050. Addressing this issue will require the enforcement of stringent global laws and the implementation of advanced monitoring systems. By 2050, the deployment of intelligent tracking systems for fishing vessels alongside the use of drones and underwater robotics could effectively validate and audit sustainable fishing practices.

The rise of sustainable land and freshwater based aquaculture will provide the majority of fish to the global population. By 2050, with the prevention of overfishing of wild fish species, the high global demand for fish will be filled by the expansion of fully sustainable aquaculture facilities worldwide. These fish farms will mainly be found on land, many of which incorporating vertical stacking of tanks to minimise land area required. For example, the Apollo Aquaculture Group operates an eight-story tall vertical fish farming facility that optimises space and resources. These aquaculture facilities will provide fully protected and controlled conditions within monitored tanks[63], connected to water filtration systems for purification and recycling. These tanks are completely separate from the oceans, non-polluting, highly efficient, and will eliminate the need for antibiotics and pesticides. Subsequently, fish will be protected from disease, microplastics, and mercury, and conditions will be optimised for growth and nutrition, providing healthy uncontaminated fish to the population. Alongside enhanced nutrition, these farms will strive to reach their "fishery potential" by 2050 for maximising yields and improving overall sustainability of the aquaculture systems. Part of this enhanced efficiency will be the gradual selective breeding of fish species for optimal growth rates and lower feed requirements.

By 2050, freshwater aquaculture is expected to contribute towards a large proportion of aquaculture practices, utilising floodplains, lakes, ponds, and reservoirs to supply a diverse range of both herbivorous and carnivorous species to the market. These systems are typically more sustainable and safer than marine aquaculture, due to reduced risk of equipment damage and enhanced environmental control. Freshwater species, which are generally smaller and lower on the food chain, usually require less feed, reducing environmental impacts and improving their cost-effectiveness. Offering a diverse range of species including anchovies, herring, and smelt, freshwater aquaculture will play a crucial role in global diets in 2050, by promoting lower-impact seafood options.

The development of alternative fish feeds is essential for fully sustainable aquaculture farms. To ensure that aquaculture is fully sustainable and economically viable by 2050, it is crucial to develop and implement alternative feeds for carnivorous fish. The overall sustainability of farming carnivorous fish has been compromised over the years by reliance on wild-caught fish for fishmeal, of which 90% are suitable for direct human consumption, with varying but improving feed conversion ratios. This reliance should be fully eliminated to protect wild fish stocks globally, completely separating land-based aquaculture from the oceans. Consequently, extensive research into fish feed alternatives that are nutritious, cost-effective, sustainable, and readily available must be carried out. Potential substitutes for fishmeal may include insects,

[63] World Economic Forum, Why more land-based fish farms could improve global food security, 2021

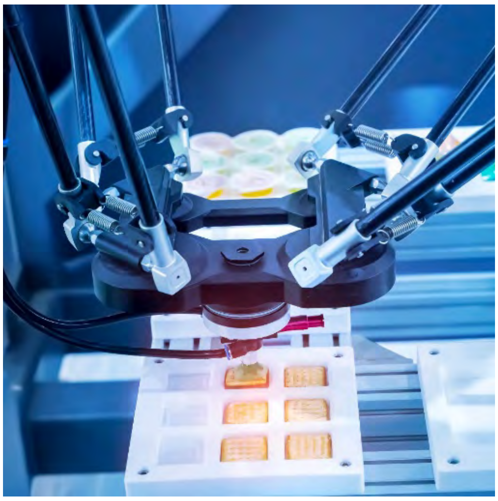
algae, and fungi, ensuring they provide adequate nutrition and pose no health and safety concerns to the fish or consumers. Many of these have already been explored, for instance Canadian firm Oberland is developing feed from black soldier fly larvae reared on industrial food waste. This could serve as an economical and sustainable feed option for salmon, replacing small wild fish species such as sardines in aquaculture fish feeds. Additionally, Swedish firm Cewatech is pioneering its alternative fish feed that utilises protein from recycled wastewater in the starch industry to produce microscopic fungi. Widespread use of these feed substitutions would facilitate the expansion of sustainable fish farming facilities, alleviating strains on wild caught fishing practices.

Smart aquaculture farms will harness advanced digital technologies. By 2050, whilst land and freshwater aquaculture will predominate, some marine-based fish farms will still operate utilising open nets within the oceans. Despite current limitations of this form of aquaculture, significant technological advancements are expected to enhance the efficiency of these systems, reduce their environmental impact, and improve animal welfare and productivity. Technologies, such as the iFarm system, could be fully implemented on a large-scale by 2050 leveraging sensors, AGI, machine learning, and the IoTT to closely monitor each individual fish. This system would enable detailed tracking of health metrics, disease presence, and growth rates. In particular, it would detect sea lice infestations, allowing for the targeted segregation and treatment of affected fish, thus minimising the use of antibiotics and reducing the risk of widespread fish loss. This precision tracking can also monitor animal welfare, hunger levels, and water quality, and determine optimal harvesting times. Tracking systems will also be able to quickly detect net breaches and locate lost species, preventing habitat disruptions from non-native fish species escaping into the environment, which has previously caused threats to local ecosystems. Such innovations would greatly benefit marine farms by mitigating their impact on the oceans and enhancing productivity. Barriers to the adoption of iFarm technologies, such as the effective protection and maintenance of underwater equipment, will likely have been resolved by 2050 alongside drastic advancements in data collection and monitoring system capabilities.

Plant-based and cultivated fish options will be readily available. By 2050, aquaculture, including marine, land, and freshwater-based farming, is expected to be the dominant form of fish production projected to supply a large majority of fish consumed globally. Alongside the expansion of sustainable aquaculture, by 2050 we are likely to see the introduction of cultivated fish products to the market made economically viable by advancements in cultivated meat technologies. Although cultivated fish may not reach the consumption levels of cultivated meat in 2050, it will help meet the growing demand for fish and provide an alternative to consumers seeking fish products that avoid intensive farming. These cultivated fish products will span a range of species, from cod fish fingers to structured salmon fillets, offering extensive opportunities for innovation in the sector. These products can be easily controlled for nutritional content, such as omega-3 fatty acids and protein, by altering the growth media components and proportions. This controlled nutrition could provide certain populations with vitamins and minerals that may be lacking in their diets and allow for the optimisation of fish species that are traditionally viewed as less nutritional in the diet.

Parallel to these developments will be significant advances in plant-based seafood alternatives, including algae-based options that offer similar omega-3 content and umami flavour profiles to traditional fish products. This could be particularly popular in raw fish products, such as sushi, which are more easily replicated than whole fish fillets. Whilst cultivated and plant-based products are expected to increasingly resemble real fish, many types of seafood, especially shellfish and crustaceans such as mussels, shrimp, prawns, crabs, and lobsters, will remain irreplaceable. Many consumers will continue to harbour a preference for real seafoods, with many cultures opting for serving shellfish and whole fish in gourmet restaurants and traditional delicacies.

Smart Food Processing, Factories, and Packaging



The food processing landscape will be significantly different by 2050. By 2050 1) food processing will be transformed to manufacture healthier food products; 2) food processing factories will largely be autonomous underpinned by AGI, IoTT, Robotics and Metaverse technologies; 3) food supply chains will become Nature Positive and Carbon Negative; and 4) sustainable packaging will have been successfully implemented.

The demand for ultra-processed foods (UPFs) will decline by 2050, which, coupled with the advent of emerging production technologies, will enable micro- and small-scale manufacturers to compete and disrupt larger counterparts in the healthy food categories**.** The rising consumer demand for healthy food products will by 2050 have had a significant impact on food processing methods adopted within factories. This trend will be driven by a growing awareness of nutritional quality, health, wellness, and longevity. This, in turn, will influence the degree to which foods are processed and how they are processed. It will also influence what people choose to eat and hence what products are manufactured. The food the population consumes impacts their health status, which ultimately impacts healthcare expenditure. Over the coming decades food manufacturers of UPFs will be under increasing pressures to formulate their products to be healthier.

UPFs are predominantly made from ingredients such as refined sugars, refined carbohydrates, hydrogenated oils, salt, nitrites, and additives such as emulsifiers, and reassembled into products. Common examples of UPFs include soft drinks, sausages, cold cuts, fast foods, breads, sauces, jams, cookies, candy bars, crisps, and cakes. As a result, they have insufficient fibre, vitamins, minerals, phytonutrients, and essential omega-3 fatty acids, but are high in components such as glucose, fructose, salt, and unhealthy oils. This has adverse impacts on the body's hormonal system, immune system, and gut microbiome, and hence a person's health and their inner biological age.

By 2050 healthier alternatives to these UPFs will be more readily available to consumers at outlet points. This shift will impact which ingredients are sourced and how food products are processed in factories. For example, Nakd Bars, which are alternative snacks available today in most stores, are produced by cold-pressing different raw ingredients such as cacao, nuts, seeds, and dried fruits together to maintain a high fibre and micronutrient content. This is a different method of production used for preparing traditional cereal bars which tend to contain added refine sugars, colourings, and emulsifiers. Furthermore, 3D-printing technology will be employed to integrate layers of nutrients into products, resulting in a final product that not only meets consumer expectations for convenience, texture, and taste, but also incorporates additional nutrients and fibre, whilst minimising unhealthy ingredients. Consequently, such advancements in 3D-Printing combined with autonomous kitchens and digital market channels will empower micro- and small-scale niche manufacturers of healthy food products to compete and disrupt larger food manufacturers. Indeed, during the product formulation phase, small and large manufacturers will be able to determine the likely health implications of the ingredients they incorporate into their products with the aid of AGI tools. Consumers will also be able to determine this very readily in 2050 using AGI-enabled applications, ultimately disrupting product innovation.

Autonomous smart factories, by 2050, will reshape the landscape of large-scale food processing facilities by integrating advanced digital technologies to enhance resource efficiency, boost productivity, enhance product quality, and improve environmental sustainability. The cornerstone of these factories will be the extensive use of automation, robotic machinery, humanoid robots, and metaverse technologies. Connected equipment with embedded sensors and AGI capabilities will perform tasks ranging from the sorting of ingredients to operating food production lines and packaging processes, giving rise to the IoTT. The IoTT will be connected to smart and robotic equipment overseen by a central AGI System, responsible for directing and optimising factory operations. Indeed, each smart factory and industrial facility within a supply chain will be interconnected through data exchange clouds. This will speed up production, create transparency of information, and increase accuracy and consistency, ensuring that every product meets stringent quality standards and consumer demand. Human operators will be able to remotely monitor and interact with factory processes through advanced interfaces that utilise augmented reality (AR) and virtual reality (VR) technologies. Such content-rich metaverse platforms will enable real-time control and engagement with manufacturing operations from any location. However, much, if not all, of the work will be undertaken autonomously. Furthermore, smart glasses will help relay real-time information, data, and visuals to onsite operators as they inspect equipment.

In the Anthropocene Epoch, by 2050 environmental sustainability will be a major focus in smart factories and their wider end-to-end supply chains. Using data gathered using IoTT, the environmental footprint of supply chains and hence the products they manufacture will be monitored and reported against the Earth's ecological ceiling. This will include their impacts on climate change, biodiversity, freshwater use, land system change, and the release of pollutants and particulates. This will drive food manufacturers to reconfigure their supply chains to become Nature Positive and Carbon Negative, directly helping to restore and maintain the Earth System's climate resiliency. This will impact where manufacturers source ingredients from, and how they operate their plants.

By 2050 it will be possible to establish a real-time digital twin of the environmental footprint of complex supply chains. Food manufacturers will be compelled to form partnerships with farmers and suppliers that are taking environmental responsibility seriously. Within the factory, advanced energy management systems powered by AGI will optimise the use of electricity and heat, significantly reducing the carbon footprint of manufacturing operations and its wider supply chain. Water recycling systems and sustainable waste management practices further enhance the environmental credentials of these factories. By incorporating green technologies, sustainable ingredients, and practices, factories in 2050 will not only meet strict environmental regulations but also appeal to consumers seeking sustainable products. This will provide them with a competitive advantage in a market increasingly focused on sustainability. These technological advancements will herald a new era of food processing that is efficient, adaptable, and environmentally responsible.

By 2050 food packaging will have adopted sustainable materials that are not only circular and compostable, but also largely derived from renewable materials. Innovations such as bioplastics, which utilise materials such as corn starch, sugarcane, or cellulose, are gaining traction. These materials breakdown more quickly than traditional plastics and have a significantly lower carbon footprint during production. Additionally, advancements in technology by 2050 will have enabled wider adoption of edible packaging made from natural food particles, such as seaweed or fruit skins, which can reduce waste entirely whilst providing novel consumer experiences. Many food products require containers and packaging that is water resistant. Such packaging tends to be complex comprising multiple layers of materials making recycling difficult. By 2050, material technology and processing will have advanced to enable the recycling of such complex packaging materials. The integration of low-cost smart technologies into sustainable packaging will by 2050 transform how consumers interact with food and other consumer products. The integration of smart technologies into sustainable packaging will change how consumers interact with food products. Smart packaging can incorporate features like QR codes or sensors that can inform supply chain partners and consumers about the freshness of the product, and details for recycling, enabling incorporation of circular economy principles into packaging supply chains. This will also be coupled by other changes in consumer behaviour and norms such as adopting reusable containers at retail outlets, be that in supermarkets, local stores, or cafés.

Food Distribution, Services and Consumption

By 2050, the landscape of food distribution, services and consumption will have undergone a profound transformation, provisioning affordable, healthier, and safer foods tailored to our individual needs. Personalised foods will be autonomously delivered via drones and autonomous vehicles straight to your door. The supermarket shopping experience itself will be revolutionised by smart AR glasses providing accurate information to the consumer, with some choosing to virtually explore the store through VR remotely. Within homes, advanced kitchen aids will prepare meals autonomously at the click of a button, alongside novel appliances including 3D printers, indoor growing units, and mini bioreactors for cultivated meat. Robotic autonomous kitchens and co-bots will be standard features in restaurants, streamlining operations and enhancing efficiency, with robotic servers able to interact with customers. Alongside this, restaurants will be able to provide customers with fully immersive and interactive experiences, improving engagement and customisation.

Ultra-Personalised Wellness and Nutrition Services. By 2050, consumer lifestyles and food purchasing preferences will be influenced by personalised insights on their health status such as heart health, biological age, hormone balance, cognition, gut health, DNA profile, immune system, and metabolic health. InsideTracker is a pioneering disruptor in this field, with the capability to provide customers with in-depth analyses of up to 48 blood biomarkers every three months. Along with additional tests such as DNA profiling and data gathered each day from smart wearables connected to InsideTracker, this builds a digital twin of each of their customers. Combined with peered reviewed science, InsideTracker can develop and recommend ultra-personalised wellness and nutrition plans, aimed at optimising health, extending healthspan, and enhancing athletic performance. By 2050, such services will become lower cost and more accessible to the wider population. They will also be able to connect directly to online retailers such as Amazon to automatically place food and meal orders and have them delivered straight to your door. Access to such powerful insights and services will alter consumer awareness and behaviour, by reducing the demand for unhealthy ultra-processed foods, propelling a shift in the ways foods are processed in factories.

Food as Medicine and Functional Medicine. Beyond its fundamental role in delivering essential nutrients and facilitating cultural and social connections, food can serve as a powerful tool in both preventing and treating various diseases. Ultra-personalised wellness and nutrition services similar to InsideTracker will help to reduce the placed on traditional healthcare systems, which operate on a reactive model of diagnosis, treat, and management of chronic disease conditions once the symptoms arise. Indeed by 2050, such services will disrupt the traditional healthcare services, enabling the adoption of Lifestyle Medicine and hence “Food as Medicine”. This will enable healthcare professionals to effectively embrace preventative care and to incorporate lifestyle interventions such as prescription foods. These can be placed into the treatment plans for patients diagnosed with chronic conditions such as diabetes type II, cardiovascular diseases, Alzheimer’s disease, depression, and autoimmune diseases. To facilitate this, healthcare providers will adopt Functional Medicine as part of their practice to identify and address the root causes of the disease through comprehensive consideration of diet, environmental factors, and other lifestyle factors.

New Category of Foods and Services for Healthspan and Longevity. By 2050, the field of longevity science will have experienced substantial growth, transforming the landscape of health and nutrition. As more individuals live to and beyond the age of 100, a new category of specialised functional foods aimed at extending healthspan and lifespan will emerge and grow in popularity. This is being pioneered by disruptors such as Blueprint, ProLon, and Nuchido. These revolutionary products are based on deep scientific research and clinical trials, that have been proven to support longevity protocols for reversing biological age. This is just the beginning, and by 2050 these products will be widespread, supporting healthy ageing, and extending healthspan and lifespan. These will form part of a new longevity market, comprising of nutritional products, personalised health apps, and longevity clinics to optimise health. Advancements in longevity science and AI will accelerate the research and refinement of longevity interventions, providing wider benefits to consumers by 2050. Longevity clinics such as Fountain Life, pioneered by Peter Diamandis MD who is founder of the XPRIZE Foundation, are optimising individuals’ health through disease prevention. They plan to utilise further advancements in technologies including AI, genomics, CRISPR, gene therapy, cellular medicine, and sensors to slow, stop, and even reverse ageing.

The growth of this new market will be driven by the population’s **increasing desire to live longer** and to maintain health and vitality well into later life. As these longevity services become more integrated into daily life, they may create a distinct demographic of people who experience improved health and wellbeing. However, consumer awareness, cultural choices, and economic factors could limit access for some individuals, preventing them from reaping the benefits of these advanced products and protocols. Although expensive today, by 2050, it is anticipated that these products and services will become democratised, making them more accessible and affordable to a broader segment of the population. This shift is expected to significantly reduce overall healthcare costs by mitigating diseases and disabilities typically associated with ageing, thereby reshaping the landscape of public health and ageing.

Grocery Delivery Services by Robots and Drones. Food orders, whether placed through health apps or directly by consumers, will be delivered swiftly and accurately using drones, autonomous electric vehicles, and robots, ensuring fresh, nutritious, and personalised groceries, meal kits, and takeaways arrive directly at consumers' doorsteps. For example, drones will be able to navigate to and accurately place deliveries within the customer's garden. This highly convenient fast delivery service will be particularly beneficial to individuals who are home-bound and unable to go food shopping. Alongside drones, small delivery bots will be able to safely navigate pavements, delivering food directly from local shops and restaurants within the community. These delivery drones and small bots could readily form part of an autonomous vehicle, able to deploy these devices in particular locations. The convenience of having personalised nutrition plans delivered by autonomous food delivery services will provide consumers with healthy well-balanced fresh meals, reducing the time required for meal planning and shopping.

In-Store Shopping Experience. By 2050, the food shopping experience will be largely transformed, to facilitate the transparency of information and ease of purchasing. As customers enter supermarkets, they will have the ability to utilise their own smart AR glasses that will display third-party information on the origin, safety, environmental impacts, and nutritional quality of food products, beyond that provided on the food labelling. This access to information will empower consumers to make more informed choices by helping to identify lower impact and more nutritional foods. For instance, consumers will be able to easily decipher between meats that have used antibiotics and meats that are antibiotic-free, through clear supply chain data. Additionally, the glasses will connect to personalised health apps, suggesting optimal food choices for individuals and encouraging healthier eating habits. This smart supermarket experience will not only elevate food transparency but will also reduce the influence of potentially misleading branding, prompting companies to enhance their sustainability and the nutritional content of their products within a competitive marketplace. Alongside the transparency of information, supermarkets will also, by 2050, provide more convenient ways for purchasing foods. Customers will be able to walk into the store, pick up all the food items they need, and leave the store with an automatic payment being made for them, with no need to scan the items. This automation will streamline the food shopping experience for consumers, providing further convenience to current checkout-free shopping involving scanners.

Brand positioning in the metaverse. In the near future consumers will widely be able to order foods and other products directly to their door from interactions within online games and virtual worlds. Brands and influencers could utilise this platform for advertisement by offering digital food vouchers or online cryptocurrencies to participants to be redeemed in store. By 2050, this could be extended further by the use of VR headsets at home, which could revolutionise the way we order food online, ushering in a new era of interactive shopping. Users will be able to step into a virtual supermarket, navigating a realistic store environment where they can easily explore and identify products. This virtual experience will be tailored to individual preferences, providing a personalised and streamlined shopping experience. The data collected from these virtual marketplaces could also inform physical stores about optimal layout and product placement, based on analysis of item popularity and viewing times in the virtual space. This innovative platform will enable customers to visualise products as they would in a physical store, enhancing their ability to make informed purchasing decisions. Additionally, this virtual space offers brands a dynamic new way to advertise and engage with consumers, transforming traditional marketing strategies. Smaller businesses will be able to utilise this virtual environment to start-up their online stores at very low-cost, able to compete with larger supermarkets. Inventory and warehouses will be managed by a third-party, such as Amazon.

Novel Kitchen Appliances. By 2050, commercial and home kitchens will likely benefit from a range of new capabilities and devices, including 3D printers, indoor growing units for salads and vegetables, and mini bioreactors for cultivated meat.

By 2050, 3D printers will be widely used by the artisanal high-end restaurants and local confectionary cake makers, for production of intricate custom-made designs and patterns within food products and meals. This will allow small businesses to thrive by enhancing consumer experience and creativity. Businesses may utilise food waste ingredients such as fruit and vegetable peels, to 3D print into new products for consumers, reducing costs and environmental impacts.

Access to 3D printers will extend beyond businesses to feature in home kitchens, allowing individuals to easily customise foods with personalised designs and textures, with no programming experience required. 3D printing at home will benefit creativity and allow individuals to tailor foods to their own nutritional or textural needs. For example, individuals with chewing difficulties will be able to harness 3D printing to produce softer foods that are easier to chew whilst remaining appetising. Furthermore, individuals will be able to customise the nutrition of food products, for instance by altering the sugar and fat content of confectionaries, or by adding supplementary nutrients to formulations. The possibilities for 3D printing are endless, providing individuals with at-home capabilities to experiment with personalised textures, designs, and nutritional content of food items.

By 2050, commercial and home kitchen capabilities could transform consumer access to fresh, healthy produce by allowing the efficient indoor growing of salads and vegetables within compact units. These units could facilitate access to these foods within urban communities with limited gardens and green spaces, and within food deserts that often rely on tinned and processed foods lacking in nutrition. They would provide these communities and businesses with chemical-free healthy produce, significantly enhancing nutrition and alleviating strains on global food imports from large-scale farms.

Cultivated meat has many possible business models projected for 2050 and beyond, ranging from production within large processing facilities, to in-house production by supermarkets and other retail outlets, and even the possibility of at-home kitchen units for meat production. Imagine a future where your home kitchen contains a mini bioreactor unit capable of producing customised fresh meat products using cells and media packets readily bought from your local supermarket. Although this vision may not be possible by 2050 due to technological constraints, it is undoubtedly a possibility by the close of the century, when meat production at home could be as normalised as producing a freshly baked loaf of bread in kitchens today.

By 2050, regardless of whether consumers opt for home-cooked meals, takeaways, or dining out, it is highly probable that their food will originate from kitchens that are either fully autonomous or partially assisted by smart technology. This integration of advanced automation is set to redefine culinary experiences across all dining formats.

Robotic Home Kitchens. By 2050, many home kitchens will be equipped with autonomous robotics and co-bots, designed to facilitate the preparation of fresh healthy meals during busy schedules. These smart kitchens will be capable of performing a range of tasks, from the retrieving and preparation of ingredients, including the precise peeling and cutting of vegetables, to the cooking of entire meals safely according to precise recipes. This automation will simplify food and meal preparation, making it more feasible for individuals to choose nutritious home-cooked meals over processed microwave meals or takeaways, even under tight time constraints. These kitchens will maintain cultural and traditional food practices by providing a diverse range of ingredients, recipes, and customisable meals. Managed through a user-friendly app, these smart kitchens will be able to work seamlessly alongside individuals, assisting cooking experiences with varying degrees of autonomy. In certain instances, operation could extend to full autonomy, allowing remote activation of at-home kitchens for completely unattended meal preparation. The accessibility of these technologies will depend on their affordability by 2050. While fully autonomous home kitchens may remain a premium feature, partially autonomous co-bots and smart devices are likely to be more accessible and widely adopted. Ultimately, the advancements in kitchen technologies and co-bots will provide significant benefits across society, particularly aiding those in assisted living who are unable to cook for themselves, as well as busy individuals who might otherwise rely on ready meals.

Autonomous Ghost Kitchens for Takeaways. Many takeaways in 2050 will be produced within a smart highly automated kitchen, many of which being characterised as “ghost kitchens”. These facilities, which are dedicated exclusively to meal preparation and takeaway services, will benefit greatly from higher levels of automation and limited need for human intervention. This form of production already reduces rental and staff costs of the facilities, providing convenient high-quality affordable meals directly to consumers, set to be further enhanced by autonomous cooking equipment. Alongside this, convenience food outlets will benefit greatly by the high levels of automation that robotics and advanced technologies will provide, with an emphasis on speed and consistency.

Advanced robotics aiding chefs in commercial kitchens. Although many takeaway and convenience food outlets will significantly benefit from high levels of automation by 2050, many high-end restaurants and local cafes will place an emphasis on collaborative robotics (co-bots) working alongside chefs and culinary staff within kitchens. These robotics will be harnessed to undertake more repetitive tasks, such as vegetable peeling and chopping, whilst skilled culinary professionals will still be responsible for cooking and presenting their bespoke artisanal meals. This hybrid kitchen experience, where co-bots aid the work of humans, will improve the efficiency of restaurants whilst preserving the unique work of chefs in global cuisines. These lower levels of automation in many dining establishments will likely be presented as a value proposition that will attract many consumers, by emphasising that the meals have been made by hand. Kitchens could also harness immersive augmented reality and cooking simulations for training new staff in preparing and cooking specific meals.

Smart Robotic Servers. By 2050, there will be robotic servers in many restaurants, helping waiting staff to serve food efficiently. We are already seeing this type of automation today, with the trialling of the "BellaBot" servers. These smart servers carry meals from the kitchen to the table by sensing any obstacles and understanding the layout of the restaurant. Then, a human waiter/waitress serves these plates to the customer, largely improving waiting times and reducing the impacts of staff shortages in the sector. By 2050, this will likely be greatly improved, with lower cost humanoid robotics working in the food sector and within restaurant service alongside humans. These robots will not just move the meals from place to place but will be able to engage with customers through conversations.

Interactive and Immersive Restaurant Experiences. By 2050, dining experiences will have evolved to allow consumers to indulge in more immersive, interactive, and customisable experiences than ever seen before. With advancements in AI and augmented reality, restaurants will be able to integrate interactive storytelling, personalised menu recommendations, and fully immersive multi-sensory environments and themes. These advancements will transform dining out from a simple meal into an unforgettable, unique experience that significantly boosts consumer engagement and increases the value of the meal. Imagine a dining experience that takes you on a captivating journey across the globe, one course at a time. As you enjoy your starter, main course, and dessert, each dish transports you to its place of origin, immersing you in the traditions of the cuisine, through use of advanced augmented reality, flexible screens, projectors, lights, and sounds. During this engaging storytelling, you can interactively customise your meal using touchscreen tabletops. Augmented reality visuals vividly display each dish option right before your eyes on the table, allowing you to explore and select your meal in a truly engaging and innovative way, with integrated AI offering the most suitable options for your preferences. These capabilities take interactive dining beyond what we see today, elevating eating out to a form of consumer entertainment and providing a memorable experience. This will boost the popularity and competitiveness of certain restaurants, with many sharing their experiences on social media and by word of mouth.

Explore our case studies, offering a glimpse into how we are helping to transform the food system.

Part III: CPI AgriTech and Novel Foods Case Studies

At CPI, we bridge the gap between academia and industry, empowering businesses to transform emerging technologies into innovative solutions that address complex challenges and unlock new opportunities. By providing expert guidance and access to state-of-the-art facilities, we reduce innovation risk, enabling faster transitions from concept to commercialisation.

We have deep technological capabilities in biologics, biotechnology, pharmaceuticals, formulation, materials and manufacturing, photonics, printed electronics, flexible hybrid electronics, and digital technologies.

We partner with businesses, including early-stage companies, to drive innovation and create tangible impacts across an array of sectors. At the forefront of cutting-edge advancements in AgriTech and Novel Foods, we are dedicated to working closely with stakeholders in developing and scaling solution that will disrupt and transform the food system. Our focus is on creating a more sustainable, efficient, and resilient food system for the UK capable of addressing future challenges.

Explore our selected case studies in this section, offering a glimpse into how we are pioneering transformative solutions.

Natural Nitrogen-Fixation Technology

azotic

Who is Azotic?

Azotic Technologies, Nottingham-based SME, is a global leader in nitrogen-fixing technologies with offices based in the UK, US, and Canada. Azotic has developed their flagship N-Fix® technology that enables crops to fix nitrogen directly from the air, promoting sustainable crop farming through a reduction in reliance on chemical nitrogen fertilisers.

Project Aim: Commercialisation of Azotic N-Fix® technology

Azotic's innovative technology utilises a unique patented strain of *Gluconacetobacter diazotrophicus* (Gd), a nitrogen-fixing bacteria capable of converting nitrogen into a usable form for multiple crop species, such as maize and soybeans. Azotic collaborated with CPI to scale-up its flagship N-Fix® technology from proof-of-concept to commercial product, facilitating its entry into the US market. CPI successfully accelerated the commercialisation process by mitigating risk, scaling-up the process, and providing large quantities of the product ready for market rollout.

How did CPI help Azotic in the scale-up of their technology?

- **Technical Expertise:** CPI provided access to its expertise in bioprocess development and scale-up, working alongside Azotic to rapidly develop a robust and scalable production process, enabling Azotic N-Fix® to enter the US market in 2019.
- **Rapid Market Entry:** CPI accelerated Azotic's journey from innovation to commercialisation by advancing their Technology Readiness Level (TRL) from 4 to 8, facilitating a rapid market entry with minimal commercial risk.
- **Scaled-up Supply:** CPI supplied Azotic with large quantities of their N Fix® product for further trials and subsequent market introduction, supporting a successful roll-out.

Impact and Value

- **Environmental Benefits:** Nitrogen fixation reduces the need for synthetic nitrogen fertilizers, thereby mitigating associated environmental impacts including reducing water pollution, improving air quality, enhancing soil health, and mitigating negative effects on human health, biodiversity loss, climate change, and ozone depletion.
- **Value to Farmers:** N Fix® is a toxin-free solution that enhances profitability for farmers by reducing fertiliser costs and supporting long-term soil health. This innovation aids farmers in transitioning to more sustainable practices, prioritising human health and sustainability, and driving the shift towards a more resilient future food system.

Spider-Inspired Sustainable Biopesticide

What is the EcoStack Horizon 2020 Project?

EcoStack is a five-year international initiative, with the aim of providing benefits to farmers, biodiversity, and the wider society, through the co-design of new sustainable cropping systems. The consortium is coordinated by the University of Naples "Federico II" (Italy), and consists of 24 partner organisations, including CPI and Newcastle University. CPI is proud to have been named as a partner within such a large European-wide consortium.

Project Aim: Testing and Scaling-up of natural biopesticide candidates

As part of the wider EcoStack Project, CPI supported Newcastle University in scaling up its newly developed biopesticide from laboratory to pilot scale. This biopesticide is made from venom proteins cloned from the tube-web spider, produced via fermentation of yeast *Pichia pastoris.* These proteins are naturally specific, and thus have the potential of targeting a crop's pests without killing non-target species. Newcastle University is working towards ensuring these identified proteins are effective when consumed by the pests, by coupling the venom peptide with a larger biomolecule that can be carried through the insect's gut wall into its tissues. CPI successfully contributed towards the testing of these new biopesticide candidates, trialling different combinations of carrier biomolecules with several venom proteins, as well as successfully scaling-up the process.

How did CPI help Newcastle University in the scale-up of their technology?

- **Bioprocessing Capabilities:** CPI leveraged its advanced fermentation facilities and bioprocessing capabilities to test three variants of the venom fusion proteins and carrier biomolecule combinations, using yeast *Pichia pastoris*. CPI utilised its capabilities with fermenting this yeast developed from previous project.
- **Scaling-Up Fermentation:** CPI successfully scaled up Newcastle University's process from laboratory-scale to pilot-scale (3500L), ensuring sufficient quantities were able to be produced for greenhouse toxicity trials.
- **Expertise in Downstream Processing:** CPI utilised its expertise to develop downstream processes for recovering and concentrating the venom fusion proteins from the fermentation process, maintaining their quality.

Impact and Value

- **Reduced Reliance on Chemicals:** These natural targeted biopesticides aim to reduce the negative impacts of chemical pesticides, by protecting pollinators, human health, and long-term soil health.
- **Value to Farmers:** Successful implementation of these biopesticides is contributing to the aims of the EcoStack Initiative by reducing costs for farmers and supporting crop yields, whilst protecting biodiversity.

Sustainable Alternative Fish Feed

CALYSTA
PROTEIN WITHOUT LIMITS

Who is Calysta?

Calysta, based in the US, is a world leader in cellular agriculture and sustainable products, creating proteins via a patented fermentation platform that uses no arable land, plant or animal products. Calysta utilises microorganisms to convert methane into highly nutritious protein for a range of feeds and food ingredients, for fish, livestock, pets, and humans.

Project Aim: Scaling up of FeedKind® Protein

Calysta collaborated with CPI to successfully scale up the production of its FeedKind® protein, an innovative fish feed ingredient ideal for species across aquaculture, including shrimp, salmon, and warmwater carnivorous finfish. This fish feed, produced via fermentation processes, has been shown to offer gut-health benefits for different fish species, such as maintaining the health of the fish's digestive and immune system. Utilising CPI's technical expertise and state-of-the-art facilities, Calysta developed its Market Introduction Facility on Teesside, the world's first single-cell protein production facility. Calysta utilised this facility to develop substantial enough quantities for feed trials, and for supporting further R&D for the commercialisation of its FeedKind® protein. Following CPI's work, Calysta is currently in the process of establishing their larger-scale production facility overseas, which will be utilised to convert CO_2 released from fermentation back into methane as a feedstock, to form a circular protein production system.

How did CPI help Calysta to establish their Pilot Plant?

- **Access to Advanced Facilities:** CPI leveraged its existing cutting-edge National Industrial Biotechnology Facilities in support of this project to supplement the bespoke elements of the demonstration plant, enabling Calysta to minimise capital expenditure and accelerate the process from design to operation.
- **Deep Technical Expertise:** CPI provided a team of experienced scientists and process engineers with technical expertise in gas fermentation technology, crucial for adapting and scaling the process of FeedKind® production to a demonstration scale.
- **Rapid Development:** Collaboration with CPI enabled Calysta to swiftly progress from the initial design stage to the construction and production phases within 18 months, achieving significant time and cost savings. Within five months of the facility's operation, it successfully produced over four tonnes of dried FeedKind® protein.

Impact and Value

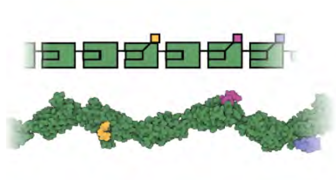
- **Secure Supply:** Successful work towards the commercialisation of an environmentally sustainable, highly nutrient dense fish feed, that offers secure supply independent of climatic variability and fishery regulations.
- **Sustainable Feed:** Contributions to the future of sustainable farming of carnivorous fish in aquaculture, developing feed alternatives that do not rely on wild-caught fish or require land-use change, aiming to preserve land and marine biodiversity.

Caf1 Growth Factors for Cultivated Meat

Who is MarraBio?

MarraBio is a spin-out from Newcastle University specialising in low-cost production of engineered bacterial protein polymers to provide bioactivity to cells at an industrial scale, with applications in food, therapy, and 3D tissue culture. MarraBio provides a multi-functional, cost-effective solution to supplying cells with the correct signals, in an easy-to-use material.

Project Aim: Developing food-grade Caf1 Protein for Market Entry



MarraBio's main ambition through their patented Caf1 protein technology is to drastically bring down the costs of cultivated meat production and to hence accelerate the UK's cultivated meat sector. Caf1 protein is produced via bacterial fermentation, and is highly customisable, able to mimic and replace many different growth factors and bioactive proteins at vastly lower costs. Caf1 aims to reduce the cost of growth factor materials to less than 1% of current costs. Collaborating with CPI and Aelius Biotechnology on a current Innovate UK project, MarraBio is striving to bring their research grade Caf1 proteins to market, ensuring they can be manufactured to meet quality and food grade requirements for the sector. The project consortia also aims to highlight the North-East as a key bio-cluster for the cultivated meat sector.

How is CPI helping MarraBio in developing food-grade Caf1 Protein?

- **Advanced Biologics Facilities:** CPI utilised its specialist Biologics facilities to develop analytical methods to assess the purity and polymer length of Caf1, providing extensive analysis to advance MarraBio's prototype products towards market entry.
- **Expertise in Downstream Processing:** CPI's Biologics team utilised its expertise in Downstream purification to suggest quality control improvements for the production process of Caf1, with the aim to manufacture them at food-grade standards.
- **Regulatory and Technical Consultancy:** CPI's Biotechnology team at our recently launched Novel Food Innovation Centre provided MarraBio with consultancy on Novel Food regulations and standards, including a HACCP analysis on current process risks, facilitating MarraBio's routes to commercialisation.
- **Investment:** CPI Enterprises (CPIE) in 2023 led the investment round into MarraBio, forming an ongoing partnership that will help the innovative start-up to scale their novel technologies, facilitating MarraBio's market entry and commercial growth.

Impact and Value

- **Economic Viability of Cultivated Meat:** Caf1 growth factors have the capability to drastically bring down the costs of cultivated meat, striving to accelerate further investment into the UK cultivated meat sector.
- **Environmental Benefits:** Cultivated Meat has many proposed environmental benefits, such as significantly lower land-use, water-use, and GHG emissions than traditional meat, protecting biodiversity, and requiring minimal/no use of antibiotics.

Algae Omega-3 Oils and Plant Proteins

Who is AlgiSys UK Ltd?

AlgiSys is an Algae Biotechnology company that takes the "fish" out of "fish oil" through their IP and proprietary strains of microalgae, producing high quality natural EPA Omega-3 nutritional oils and vegan plant protein. AlgiSys is commercialising its sustainable fermentation process, initially for the aquaculture, supplement, animal and pet nutrition markets, and eventually for the food, beverage, cosmetics and pharmaceutical markets.

Project Aim: Scale-up of Algae Fermentation Process

AlgiSys estimates that over 15 years of research and millions in investment have been dedicated to developing their microalgae fermentation process for the production of EPA Omega-3 and plant protein. This versatile technology has diverse applications, ranging from algae powder used in fish feed and pet food, to algal oil used in supplements and cosmetics, as well as nano-encapsulated and plant protein ingredients for food and drink products, with future prospects extending to pharmaceuticals. Currently, the main source of EPA Omega-3 in the market is from wild fish, 70% of which comes from Peruvian anchovies. These are affected by climate vulnerability and El Nino events, with demand for omega-3 currently outstripping supply. AlgiSys goes right to the source of omega-3, Algae, providing a non-GMO, non-fish, sustainable plant-based source. AlgiSys is collaborating with CPI to scale-up its process to demonstration scale and eventually full commercial scale, initially for Scottish salmon feed.

How did CPI help AlgiSys in the scale-up of their technology?

- **Expertise in Process Scale-up:** CPI is utilising its expertise in bioprocess development and its previous experience in fermentation, microalgae and omega-3 to scale-up and commercialise AlgiSys' technology using its IP and proprietary strains.
- **State-of-the-art Facilities:** CPI is leveraging its existing cutting-edge biotechnology equipment and analytical capabilities for product finalisation and optimisation.
- **Data Analytics to De-Risk:** CPI conducted comprehensive analysis of the fermentation process utilising advanced software, providing performance insights to de-risk at the process larger scales.

Impact and Value

- **Sustainable Alternative Fish Feed:** AlgiSys' technology addresses EPA Omega-3 and plant protein demand-supply challenges by replacing fish oil and fishmeal, offering an affordable, low-emission domestic supply of alternative aquaculture feeds.
- **Plant-based Source:** Offers a new vegan source of EPA Omega-3 and plant protein, rather than inactive ALA Omega-3 in vegan supplements and foods, promoting heart and joint health, and free from contaminants e.g. microplastics, PCBs, mercury, lead.
- **Omega-3 Enriched Foods:** AlgiSys plans to incorporate its EPA Omega-3 into various food items in the future e.g. boosting omega-3 content in meat, like poultry, via feed supplementation offering health benefits to consumers and adding value for farmers.

Probiotic Supplement for Formula Milk

Who is BoobyBiome?

BoobyBiome is UK-based biotech startup focused on improving infant health by harnessing the power of the breast milk microbiome. Founded by three female scientists, the company is developing innovative products to provide the benefits of breast milk microbiome to all babies. They are addressing the rise in infant diseases linked to low breastfeeding rates and underdeveloped microbiomes, to provide our future generations with a better start in life.

Project Aim: Scaling up and optimisation of supplement

BoobyBiome has developed a ground-breaking product, a next-generation supplement for babies, containing probiotic microbes isolated from breast milk and prebiotic fibres to support bacterial growth. These supplements are easily added to baby formula or breast milk to boost the gut health of newborn babies, providing short and long term health benefits. This is so important because many women are unable to breastfeed, and this supplement ensures that all babies can benefit from the protective properties of the breast milk microbiome. BoobyBiome is collaborating with CPI to commercialise their innovative product, by optimising bacterial growth conditions for their breast milk microbes and establishing scalable methods for producing the supplement.

How did CPI help BoobyBiome in the scale-up of their technology?

- **State-of-the-art Equipment:** CPI utilised its advanced equipment in Biologics including high throughput bioreactor systems for process development, and molecular analytical characterisation methods, resulting in an analytical toolbox for product characterisation.
- **Expertise in Microbiome Therapeutics:** Utilising its expertise, CPI conducted feasibility study on co-culturing multiple species of bacteria at scale, establishing a robust and efficient manufacturing process for a multi-strain probiotic product.
- **Fermentation Scale-up:** CPI successfully developed, optimised, and scaled up the bacterial fermentation process for the infant milk supplement to a 10L scale, with an ongoing collaboration to complete the preclinical program and prepare for launch.

Impact and Value

- **Infant Health and Wellbeing:** This supplement boosts the gut health of newborn babies and pre-term infants, supporting early immune system development, aiding digestive health, lowering risk of long-term diseases. This allows women who cannot breastfeed to still provide the benefits of breast milk to their newborns.
- **Researching an Understudied Area:** This project is paving the way for further research into gut microbiome supplementation for infant milk, which is an extremely important but under-studied area, to improve wellbeing and healthy development of our next generation of infants.

Compostable Seaweed Bio-Packaging

Who is Oceanium?

Oceanium is a UK-based start-up that utilises sustainably farmed seaweed to develop and produce innovative, functional seaweed-based ingredients for food, wellness, and materials to benefit people, health, and ocean health. Oceanium's mission is to "Kelp the World®" by promoting sustainable seaweed farming and supporting the UK's blue economy, whilst reducing plastic pollution and providing wider environmental and social benefits.

Project Aim: Development and testing of Oceanware™

Oceanium collaborated with CPI to develop and test initial formulations for its home-compostable and marine-safe seaweed bio-packaging, Oceanware™. This innovative solution aims to address the escalating plastic pollution crisis by providing a safe and effective alternative to plastic packaging. To work towards this mission, CPI conducted comprehensive physical testing to produce samples of Oceanware™ that meet the physical requirements for food packaging. This involved the in-depth analysis of several seaweed compounds and formulations to compare with current bioplastics available on the market. The long-term goal is for Oceanware™ to be fully compatible with existing machinery, packaging converters, and composting systems in the UK, ensuring a sustainable end-of-life process.

How did CPI help Oceanium in the development of Oceanware™?

- **Expertise in Bioprocessing:** CPI offered its expertise in process development and utilised its state-of-the-art facilities to successfully develop an initial formulation alongside Oceanium for the first iteration of Oceanware™ bio-plastic samples.
- **Iterative Formulation Testing:** CPI carried out physical testing of Oceanware™ samples against existing bioplastics on the market, showing promising results, and identifying areas for further development, which Oceanium will utilise when refining the formulation for product trials.
- **Access to Funding:** By working with CPI, Oceanium secured funding for the development of Oceanware™ through CPI's Project IMPACT, part-funded by the European Regional Development Fund (ERDF), allowing such research to take place.

Impact and Value

- **Environmental Benefits:** Seaweed Oceanware™ is an environmentally friendly alternative to plastic that not only eliminates plastic pollution, but also reduces ocean eutrophication, requires no land, fertiliser, pesticides or freshwater, improves ocean biodiversity, and absorbs CO_2.
- **Job Creation:** Sustainable seaweed farming contributes to the "blue economy", promoting responsible coastal management and creating jobs in rural coastal regions. Oceanium is aiming to develop the UK's seaweed farming industry to create a sustainable supply chain.

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