ECONOMIST IMPACT

Food 4.0

Technology in Agriculture and Food

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SGINNOVATE

Preface

This report is built on a research programme undertaken by Economist Impact, and commissioned by SGInnovate, between July and October 2021. It evaluates the adoption and potential of emerging technologies in the agriculture and food sectors. The report is based on an extensive literature review, a primary research survey and an expert interview programme.

The project management team included Charles Ross, Pratima Singh, Ritu Bhandari, Aayushi Idda Sharma, Shubhangi Pandey and Ravija Harjai. Additional support was provided by Camilo Guerrero (writer), Kerry Hughes (editor) and the Economist Impact design team.

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Executive summary

Agricultural production and food supply are facing unprecedented pressures. Decreasing per-capita arable land and extreme weather conditions are adversely impacting agricultural output. The covid-19 pandemic has exacerbated the existing stress placed on the global food system, particularly due to disruptions in food supply chains. A growing population, rapid urbanisation and changing consumption patterns will continue to increase pressure on food systems going forward. Innovative technologies offer solutions to increase agricultural productivity and support the drive for greater sustainability under these rapidly evolving circumstances. However, the wider adoption of such technologies faces challenges such as high costs and regulatory constraints.

This report, written by Economist Impact and commissioned by SGInnovate, explores the drivers and challenges influencing the adoption and deployment of innovative and emerging technologies, across the food value chain. The report is interspersed with insights from a survey conducted by Economist Impact of 100 business leaders in the agri-food industry from Australia, Israel, the Netherlands, Singapore, Switzerland, the Philippines and the US, along with interviews conducted with business leaders and industry experts in the sector.

Key findings

The combined impact of land degradation and rising food demand is driving a food security crisis. Businesses are adopting emerging technologies that can improve agricultural productivity through effective big data analysis. For instance, precision farming uses a combination of emerging technologies like artificial intelligence (AI), the Internet of Things (IoT) and drones to collect, monitor and analyse big data. The data analysed is used to accurately predict the need for different resources at every stage of agricultural production, thereby preventing wasteful resource use and leading to efficient production. According to Economist Impact's survey, 31% of businesses are interested in adopting AI in the next five years, in addition to the 28% that have already adopted the technology.

Effective use of data is helping to address the issue of food waste, which remains an important challenge in tackling the food security crisis. An estimated 30% of the food produced for human consumption globally is lost or wasted along the food supply chain. A lack of accurate data is a major challenge in preventing food waste. Deploying AI in inventory and supply chain management can enable greater visibility of the freshness of food products,

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while AI-driven forecasting methods can allow accurate prediction of food demand in the market. Supportive policies and regulations that encourage collection and monitoring of data on food waste can assist in wide-scale adoption of these solutions.

New ways of producing food will be needed to meet rising demand in the future. For instance, vertical farming, an indoor farming technique that produces crops vertically at multiple levels, can mitigate the challenge of limited agricultural land. The Economist Impact survey finds that, of the technologies included in the survey, indoor or vertical farming is expected to see the highest jump in adoption by businesses, with Singapore showing the greatest interest (38.9%).

The economic benefits of technologies play a critical role in business adoption; however, many organisational factors drive and hinder the adoption of new technologies. Almost four in five business leaders (79% of respondents) in the Economist Impact survey give high priority to the need to improve business operations and save costs as drivers for technology adoption. Some technologies, such as smart farming methods like precision farming, are helping to reduce farm machinery and input costs. High initial or overall costs (41%) and a lack of funding (34%) appear to be the main internal barriers to technology adoption among companies in the sector. Other organisational challenges limiting the adoption of new technologies include lack of in-house talent and expertise, rigid structures requiring long approval processes, and organisational inertia.

Agricultural innovations through agri-biotechnology, like the genetic modification of plants, can increase agricultural resilience. Regulatory approval and consumer acceptance will determine their pace of adoption. Genetic modification can engineer plants to enable them to survive extreme climate events such as drought, and can increase crop resistance to pests. Of business leaders surveyed by Economist Impact, 77% consider developing climate resilience, such as farming in drought conditions, an important factor influencing their decision to adopt emerging technologies. In the US, despite low consumer awareness, there is a high prevalence of consumption of genetically modified (GM) crops. In countries like Israel, where consumers don't have strong opinions on this topic, regulatory barriers inhibit the production of GM crops. In the EU, both limited consumer acceptance and a strict regulatory framework have led to limited adoption of these crops. Consumer hesitancy also remains high in Singapore due to lack of consumer awareness and education.[1]

Alternative proteins can help reduce agricultural emissions but are heavily influenced by regulatory hurdles and consumer approval. This sector, which includes artificial meat made from plants, proteins fermented using live microorganisms, and lab-grown meat, promises to eliminate a large share of agricultural emissions by replacing livestock.[2] In Singapore, where lab-grown meat is available for consumers to try, acceptance has been relatively high. Governments worldwide will play a critical role in promoting the global adoption of these alternatives through supportive regulations and by educating consumers about the products. Where these alternatives are accepted, more investment in infrastructure will be required since there is currently no cost-effective solution to scale up these meat alternatives.

The covid-19 pandemic has changed consumer behaviour, visible in a boost in demand for personalised nutrition. Given the serious, and in many cases, lasting health implications of covid-19, consumers are increasingly looking to "food as medicine" to boost immunity and build resilience. According

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to one global survey, personalised nutrition is a key consideration for 64% of consumers when purchasing food and dietary products.[3] Several emerging technologies are enabling personalised nutrition, such as cell-culture, which can produce meat fortified with minerals and nutrients, and 3D printing, which can produce food with nutrition profiles customised to the consumer's needs.

Emerging technologies such as blockchain in the food supply chain are being adopted by businesses which are prioritising food safety in response to consumer concerns. Economist Impact's survey reveals that 78% of respondents considered a growing focus on tackling food safety issues in the supply chain as an important factor influencing their decisions to adopt emerging technologies. Blockchain provides end-to-end visibility of the supply chain and helps businesses trace the source of food in order to manage food safety issues. The technology can enable each stakeholder in the supply chain to review the status of a transaction, identify errors, and hold counterparties to account for their actions. In addition to high initial investments, the need for adoption of blockchain by all stakeholders in the supply chain remains a barrier to large-scale adoption. Governments and regulatory bodies could assist by implementing industry-wide rules and standards for blockchain adoption.

Building a successful innovation ecosystem—one that includes academia, startups, corporates and governments—is key to accelerate development and drive the uptake of new technologies. For an ecosystem to be effective, there must be equal attention given to collaboration between stakeholders for the adoption of emerging technologies. As per Economist Impact's survey, the most common approach taken by companies to gain access to emerging technologies is through collaborations with academia (57%), followed by collaboration with startups (50%). Academia is a source of cutting-edge knowledge and talent for cost-effective research and novel product development. Similarly, large corporations acknowledge that startups are driving innovation. Successful collaborations between startups and corporates rely on the alignment of priorities and operation styles, as well as a strong team behind the startup. Government support is equally vital as it is positioned to deliver better infrastructure, research guidance and capital.

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Introduction

Warmer climates have contributed to declining agricultural productivity in recent years.[4] Globally, 33% of the world's farmland is moderately to highly degraded, and 24bn tons of fertile soil are being lost each year, largely due to unsustainable agricultural practices. If current trends continue, 95% of the earth's land area could become degraded by 2050.[5] These issues highlight the close interlinkages between food security and sustainability.

The covid-19 pandemic exposed the vulnerability of global agriculture and food systems. An increasing number of countries reported growing levels of food insecurity, reversing years of development gains.[6] Border and transport restrictions disrupted food supply chains, while agricultural farms were affected by labour shortages. While consumer demand for retail food soared, food sales in hotels and restaurants collapsed, requiring drastic changes in how the retail and consumption side of the supply chain operates.[7]

Food supplies will face unprecedented pressures in the coming decades. A growing population, accompanied by increasing urbanisation, is expected to drive a 35–56% increase in food demand between 2010 and 2050.[8] Disease outbreaks like covid-19 and African swine fever have drawn increased attention to the resilience of the food supply chain, and amplified the demand for fresh and local food products.[9]

Innovative solutions developed through emerging technologies could help to address these challenges. From genetic modification of crops to blockchain in the food supply chain, these solutions are improving the efficiency, resilience and traceability of food systems. However, despite the potential of these new technologies, their levels of adoption remain insufficient to tackle current and future food security, safety and sustainability challenges. While some technologies require a very high initial investment, others currently lack regulatory approvals and consumer acceptance.

Due to the large-scale, global nature of the agriculture and food sector, many forces are involved in the success of an innovation. At the initial stages, startups and universities play an important role in creating a novel solution. Governments and accelerators offer financial support and guidance as well as an enabling regulatory environment; while large companies enable scalability and market adoption.

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This report explores the extent of the adoption of emerging technologies and their potential to solve the challenges facing the agriculture and food sector, and highlights best practices in successful adoption by analysing challenges and drivers. It combines analysis from an Economist Impact survey of 100 business leaders[10] from the agri-food industry, interviews with business leaders and industry experts in the sector, and an extensive literature review. This report:

- Highlights the extent and market size of adoption of emerging technologies in the agri-food sector;
- Analyses the challenges to and drivers of adoption, including organisational factors, the regulatory environment and consumer perceptions;
- Presents a range of best practices from countries that have encouraged innovation in the sector;
- Evaluates the current stakeholder ecosystem and the successful interlinkages between them that enable market adoption of emerging technologies;
- Considers the implications for technology adoption in the agri-food sector in the future, highlighting factors and trends that will play a key role in their adoption.

This research programme focuses on the adoption of emerging technologies in agricultural production (agritech), the agriculture and food supply chain (agri-food supply chain), and consumption (foodtech).

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Overview of the current state of technological adoption in agritech, agri-food supply chain and foodtech

Global trends in sustainability, healthier diets and food safety are driving increasing investments in the agriculture and food sector. Governments across the world are encouraging innovation in the sector to meet the growing food demand and tackle the rising pressure on agri-food systems. Adoption of emerging technologies by the private sector is becoming a business need as companies increasingly target food safety, sustainability and efficiency as their key objectives.

Emerging technologies offer novel ways to address pressing issues in the agriculture and food sector. Against a backdrop of shrinking arable land for agricultural production, technologies that can increase the productivity of land and enable new ways of farming with limited natural resources are becoming crucial. As food safety becomes an increasing priority for businesses, consumers and governments, technologies that enable transparency and traceability of food supply chains are seeing higher growth. Changing consumer preferences and habits are driving innovations like alternative meat and online deliveries in foodtech. This section provides an introduction to emerging technologies in the sector, based on their market value, rates of adoption and investment, and their potential for growth. The Economist Impact survey, literature review and expert interviews were used to shortlist these technologies.

Agritech: Agri-biotechnology, smart farming and novel farming methods

A growing global population, rising food insecurity and increasing pressure on natural resources are focusing attention on improving agricultural production. Agritech involves the application of technologies that enable cleaner, greener and efficient agricultural production.[11] It includes technologies such as gene editing, IoT sensors, automation, big data analytics and indoor farming.

Global venture capital investment in agritech companies doubled between 2019 and 2020, reaching US$5bn, driven by biotechnology and indoor agriculture. Strong investor appetite for these two segments reflects the market response to supply chain disruptions caused by the covid-19 pandemic. Shifting consumer preferences favouring local and fresh produce are also driving increased interest in these sectors.[12]

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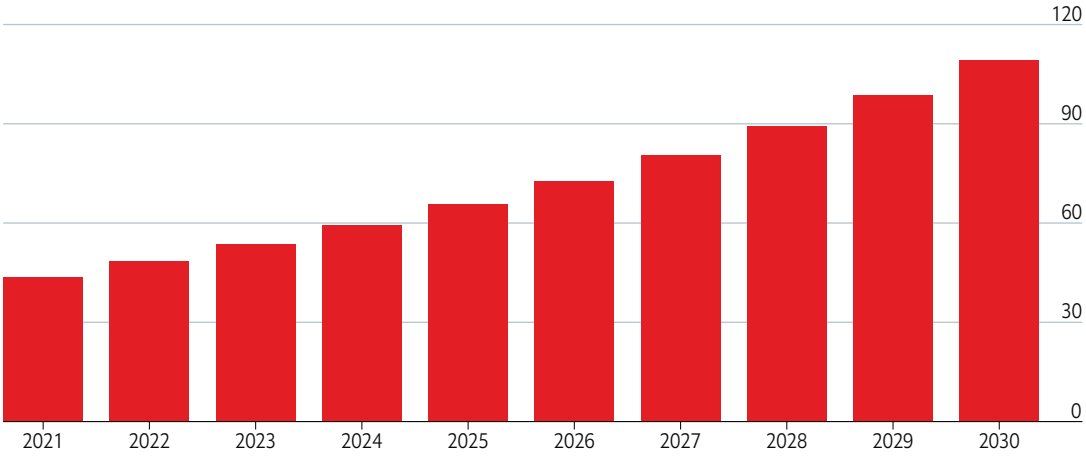
Agricultural biotechnology (agri-biotechnology) is enabling agricultural adaptation and mitigation by increasing crop resistance (to pests) and resilience (to extreme weather events). It includes the application of traditional breeding techniques and genetic modification that can alter living organisms, or parts of organisms.[13] Genetic modification can engineer plants to develop resistance to diseases and pests, thereby reducing the use of pesticides. The value of the global agri-biotechnology market[14] currently stands at about US$43.8bn[15] and is expected to grow at 10.7% between 2021 and 2030[16] (Figure 1).[17]

Figure 1: Agri-biotechnology estimated market growth by value, 2021-30
(in billion US$)



Sources: Prescient & Strategic Intelligence;[18] Economist Impact.

Smart farming is another growing area due to its ability to advance productivity on agricultural farms. It deploys technologies like drones, IoT sensors, remote sensing, and precision farming to increase farm efficiency, optimise labour and minimise costs.[19, 20] The smart agriculture market has been valued at US$15bn[21] in 2021 and is expected to grow at a rate of 9.8% year on year from 2020 to 2025.[22]

In 2019, precision farming accounted for the largest share of the smart agriculture market, at approximately 46%. It involves collecting, monitoring and analysing large agricultural data to accurately predict and optimise resource use in production,[23] and studies indicate that precision farming techniques can reduce farm machinery and input costs by up to 75% in some cases.[24] Agricultural data—related to soil moisture, air temperature and humidity, and crop and livestock health—collected using IoT, can be analysed using machine-learning algorithms to generate insights that can optimise farm management. Drones can be equipped with cameras and GPS technology to conduct field surveys for data collection.[25] Robotics are being used to automate tasks such as seeding, harvesting and watering, which can overcome labour shortages.[26] Within harvesting, while recent innovations like the development of crop-harvesting robots with a workload capacity equivalent to 30 human labourers seem

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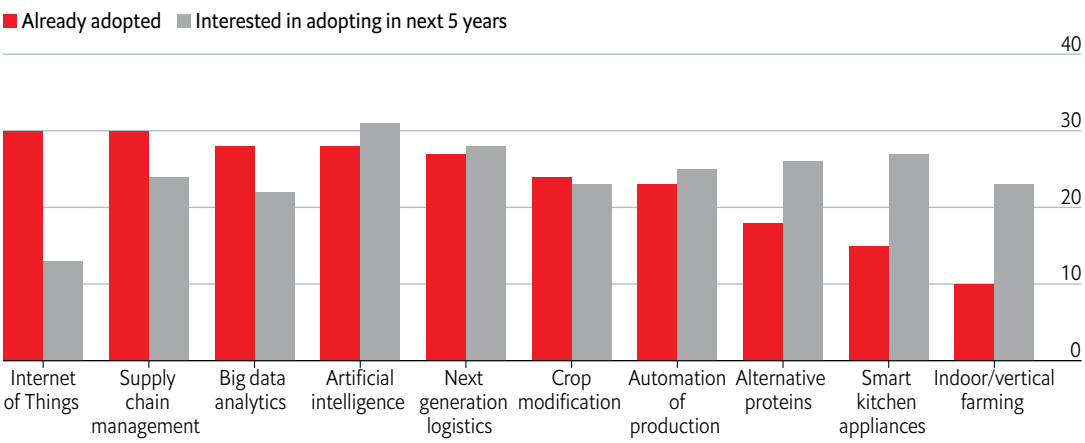
promising, the need for manual dexterity in picking crops potentially limits the prospects of automation.[27]

Novel farming methods, which involve growing crops in an indoor setting in a limited space, offer solutions to the issue of shrinking arable land. Among the 100 business leaders surveyed by Economist Impact, 10% have already adopted and 23% are interested in adopting indoor or vertical farming technologies in the next five years (Figure 2).[28] Pandemic-led supply chain disruptions and the increasing food dependency concerns of import-dependent countries has accelerated interest in this technology.[29] Vertical farming is a type of indoor farming technique that requires limited or no pesticides. This technology includes entirely insulated indoor operations, often producing crops on multiple levels using electrical lighting, like light-emitting diodes (LEDs).[30, 31] LEDs can be adjusted to create light wavelengths specific to plant needs.[32] Such farming techniques involve the integration of multiple emerging technologies like IoT, AI, robotics, and big data analytics, to support crop cultivation, especially when facing agricultural resource constraints.[33] In 2018, Asia-Pacific and North America collectively accounted for almost three-quarters of the total global vertical farming market size by revenue.[34]

North America, which includes the US, Canada and Mexico, dominates the global agritech market, driven by agri-biotechnology, novel farming and farm management systems, and sensing and IoT products, resulting in a surge in agritech startups in the region.[35] The US currently accounts for 33.6% of the global market for smart farming. This market growth is driven by supportive government initiatives and regulations, as well as concerns around water conservation.[36] In countries with limited arable land like Singapore,[37] ongoing research and innovation is leading to experimentation with tools to monitor plant health. These tools enable the application of precision farming techniques on urban farms, which require rapid identification of precise plant tolerances to enable optimal growth.[38]

Figure 2: State of adoption and interest in adopting emerging technologies
Which of the following technologies has your organisation adopted or is interested in adopting in the next five years? (%)



Source: Economist Impact survey.

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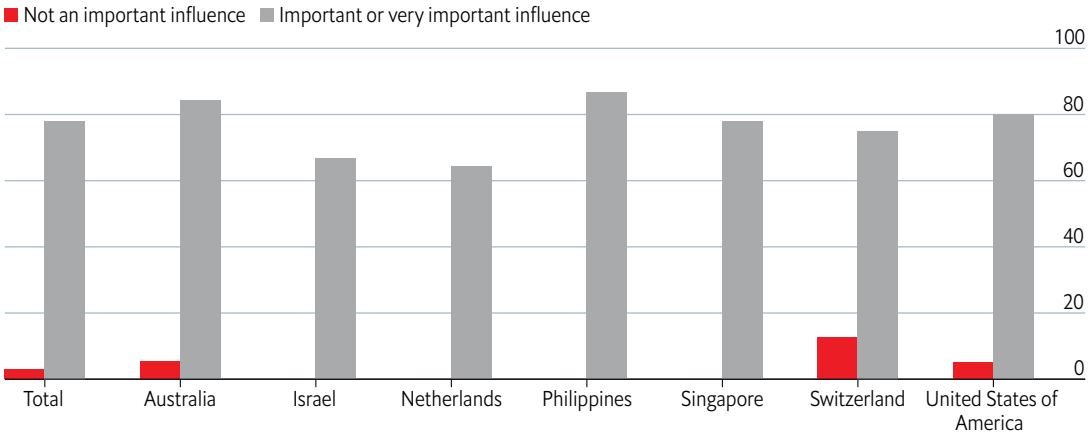
In the survey, 23% of respondents expressed interest in adopting indoor/vertical farming over the next five years, with the greatest interest in Singapore (38.9%), followed by the US (30%). The expected jump in the adoption of indoor/vertical farming from 2021 to 2026 (Figure 2) is the highest among all technologies included in the survey.

Agri-food supply chain: Blockchain, food safety testing and AI

From field to fork, the agri-food supply chain accounts for 10% world GDP and employs an estimated 1.5bn people. The agri-food supply chain covers the flow of food products from the post-production to pre-consumption stage.[39, 40] With increasing globalisation, supply chains face increasing risk of disruption and contamination as they cover multiple countries and regions, involving many stakeholders and processes, and moving away from their operations in silos.[41] Food safety in these supply chains is receiving high business priority and growing public attention, influenced by multiple disease outbreaks such as Escherichia coli (E. coli) and African swine fever.

Innovation has become critical in managing food safety and quality in a large and dispersed food supply chain. According to Economist Impact's survey, 78% of respondents consider a growing focus on tackling food safety issues in the supply chain an important factor in influencing the decision to adopt emerging technologies.

Figure 3: Food safety issues drive adoption of technology
How important an influence does a changing business strategy, for example a growing focus on tackling food safety issues in the supply chain, have on your organisation's decisions to adopt emerging technologies? (%)



Source: Economist Impact survey.

Food supply chains can be a source of foodborne diseases. Businesses are therefore conducting food safety testing, using technologies that can identify and test the quality and safety of products at each step of the supply chain. The food safety testing market is projected to grow at 7.9% year on year until 2026.[42] Increasing consumer scrutiny of the industry's compliance with food safety standards, accelerated by the covid-19

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pandemic, is one key driver for the market growth.[43] In a 2020 survey conducted by the International Food Information Council among US consumers, over 50% of respondents ranked foodborne illness from bacteria and the presence of chemicals as a top food safety issue.[44]

Innovation in food safety is critical as sole reliance on manual testing may be prone to human error. It can be difficult to smell, taste or see (without a microscope) pathogens.[45] Optical scanning techniques pick up bacterial and faecal contamination and alert the user to possible contamination by vibration and lighting, removing the need for visual inspection by humans.[46] Rapid testing technologies, with a short turnaround time, high accuracy, sensitivity, and an ability to test a wide range of contaminants, are estimated to account for the fastest growth potential.[47] Examples include near-infrared spectroscopy (NIRS, for the quantitative determination of major constituents in food products) and nuclear magnetic resonance (NMR, a technique using the magnetic properties of certain chemical nuclei for detection of chemical contaminants).[48]

Food traceability can also help businesses identify the source of a food safety problem.[49] Blockchain provides real-time and end-to-end visibility of supply chains.[50] For example, the use of blockchain on a tomato farm in the US was piloted to track ripeness, colour and sugar content, resulting in detailed documentation of the supply chain, as well as a reduction in spoilage.[51] When adopted at a larger scale, blockchain makes it easier for each stakeholder involved in the supply chain to review the status of a transaction, identify errors, and hold counterparties to account for their actions. In light of these potential benefits, the use of blockchain in the agriculture and food supply chain is projected to grow at 48.1% year on year from 2020 to 2025.[52] However, since a successful blockchain network relies on its adoption by all players in the supply chain, the lack of consistent industry standards and regulatory frameworks around the technology can be a challenge.[53]

In addition to food safety, the agri-food supply chain poses a food security challenge. An estimated 30% of the food produced for human consumption globally is lost or wasted along the supply chain.[54] AI is helping businesses to reduce or eliminate food waste.[55] For example, deploying AI in inventory and supply chain management can enable greater visibility of the freshness of products. This in turn helps retailers streamline inventory management, reducing waste associated with over- and understocking.[56] AI-driven demand forecasting systems can assist in the accurate prediction of market behaviours and trends. These systems combine historical data with data on weather events, lifestyle and shopping patterns, or marketing initiatives to make more accurate predictions.[57] Among 100 business leaders surveyed by Economist Impact, 28% have adopted AI and 31% plan to adopt the technology in the next five years.

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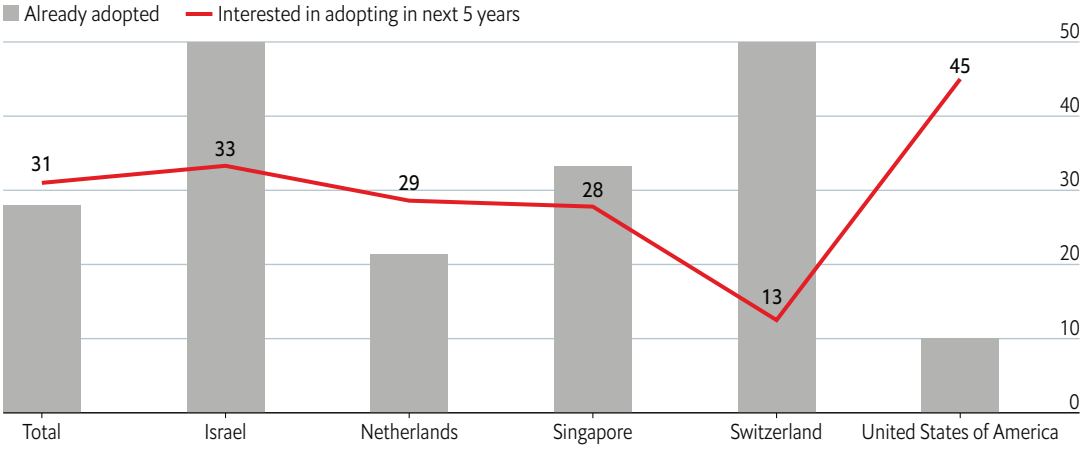
Figure 4: Change in adoption of Artificial Intelligence
Has your organisation already adopted or is interested in adopting artificial intelligence in the next five years? (%)



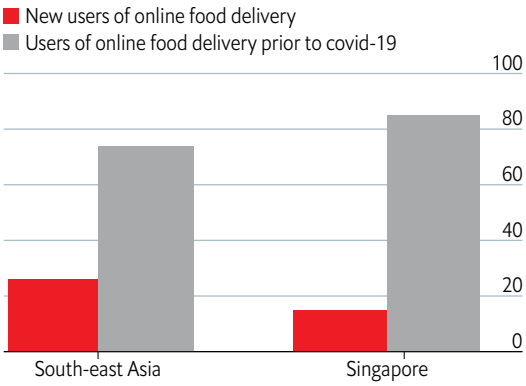
Source: Economist Impact survey.

Foodtech: Online delivery and alternative proteins

While the agritech sector focuses primarily on agricultural production, foodtech is focused on the retail and post-retail part of the supply chain. Venture capital investment in the foodtech sector skyrocketed from around US$60m in 2008 to more than $1bn in 2015.[58] Despite covid-19, investment in the sector surpassed $20bn in 2020.[59]

The covid-19 pandemic has accelerated the online food delivery segment within foodtech. The heavily hit food and hospitality industries, which were disrupted by lockdowns, quickly moved to providing online food delivery services to meet consumer demand.[60] Oddbox, a UK delivery platform specialising in fruit and vegetables from local farms, saw a fourfold increase in sales revenue in 2020.[61] In a South-east Asia survey conducted by Euromonitor International, with a sample size of 1,800, one in four (26%) surveyed consumers in the region was a new user of online food delivery services during the pandemic.[62] Online food delivery is the leading service under foodtech,[63] attracting more than 48% of total investments, driven by unicorns such as DoorDash and Deliveroo, headquartered in the US and UK, respectively.[64]

Figure 5: Growing demand for food delivery in South-east Asia after covid-19
(%)



Note: South-east Asia refers to Indonesia, Malaysia, Singapore, Thailand, the Philippines, and Vietnam.
Source: Euromonitor Survey.[65]

The combination of AI, robotics and automation is transforming food delivery methods. These technologies collect vast amounts of data for food companies, giving

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detailed insights about their customers, identifying the nuances in customer behaviour and individual product demand.[66] The sector is also experimenting with robotics for food delivery. In 2018, food delivery robots in the UK utilised cycle and pedestrian paths for trials as a robot-friendly testing ground. Throughout the pandemic, a fleet of robots in the UK has completed over 100,000 autonomous deliveries. However, the adoption of robots for food delivery faces challenges due to a lack of complete autonomy as they need to be monitored by a supervisory team; moreover, carrying capacity limits their widespread adoption. The impact on human jobs is another concern.[67]

This growth in online delivery has also led to an influx of cloud kitchens—restaurants operating without dine-in services and taking only online orders through mobile apps. To lower costs of operation, such as real estate and labour costs, cloud kitchens replace human labour with smart kitchen and restaurant technology in order to function efficiently.[68] For example, sensors help restaurants track the number and type of delivery containers needed during busy periods, or monitor the number of eggs in a refrigerator.[69] Smart kitchen appliances, such as smart refrigerators, are also finding a place in households as a result of the increase in demand for energy-efficient appliances with user-friendly interfaces.[70]

The movement towards sustainability in the food sector is driving the alternative protein market in foodtech. Studies estimate that adopting alternative proteins can eliminate 60% of agricultural emissions.[71] In the Economist Impact survey, 26% of business leaders stated that they would be interested in adopting technologies in alternative proteins over the next five years—indeed, this is one of the top choices out of the ten emerging technologies surveyed, behind AI and IoT, and closely aligned with smart kitchen appliances. The trend is driven by the twin benefits of huge business potential and the environmental gains.[72]

The plant-based meat industry, which includes products made from plants such as soy or peas that imitate meat, alone raised US$2.1bn in 2020. Cultivated meat, also known as cultured or lab-grown meat, which is produced through (stem) cell and tissue culture, attracted more than US$360m in investments in 2020, which is six times the amount raised in 2019.[73] While consumer demand is driving this market, many consumers remain reluctant to try these products due to a lack of familiarity with the environmental and health benefits.[74]

The current state of regulations for alternative proteins lags behind market investment, and there are few standardised best practices consistent with regulation.[75] However, there is some progress, with Singapore becoming the first country to grant approval to lab-grown chicken meat in 2020.[76] In many parts of the world, alternative proteins, particularly cultured meat, continue to face regulatory barriers and long approval processes. Regulatory progress will play a determining role in transferring these alternative protein solutions from labs to markets.

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Challenges and drivers associated with technology adoption

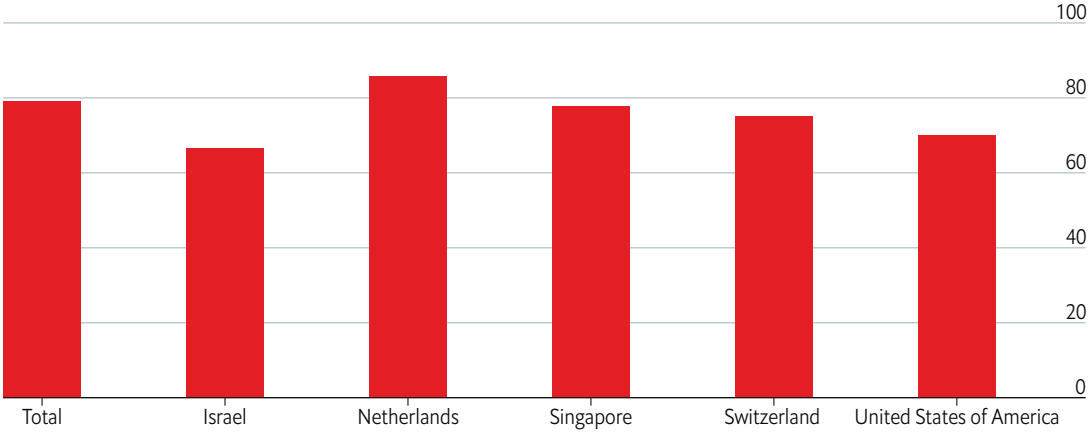
Adoption of emerging technologies by businesses in the agri-food sector is intertwined with the organisational factors—like the economic benefits of the technology and the specific problem it solves for a business—and external factors driven by the various players in the innovation ecosystem—notably, regulatory bodies, consumers and competitors. This section examines the key challenges and drivers of technology adoption in medium and large companies, such as organisational factors, regulatory environment and role of customer preferences, and highlights best practices.

Organisational factors play a crucial role in the adoption of new technologies

The Economist Impact survey highlights the influence of organisational factors in the adoption of emerging technologies: 79% of business leaders give high priority to the need to improve business operations and cost savings (for example, through precision farming and optimisation of water usage); and 78% consider technology essential for changing business strategy and increasing

Figure 6: Improving business operations drive technology adoption in companies

Does improving business operations (eg, cost savings through precision farming and optimisation of water usage) have an important or very important influence on decisions to adopt technology? (%)



Source: Economist Impact survey.

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food safety issues in the supply chain. However, technology deployment can be challenging and disruptive. Many companies may face organisational inertia, challenges in securing funding for new technologies, and rigid structures that negatively impact the pace of innovation.

Business needs drive adoption of emerging technologies

Expert interviewees consulted in this study highlight that solving existing problems and addressing specific business needs are key drivers of the adoption of emerging technologies. "We are not deploying technology just because technologies exist, we are deploying technology to solve particular business problems," notes a global supply chain expert from a leading multinational company in the consumer packaged goods space. Jonathan Chan, Digital Advisor APAC at Cargill, concurs with this view: "The reality is that why we innovate, and why we find new ways of doing things is to solve existing problems that we have in the business. It is relatively simple to develop the technology these days, but finding the problems and committing the resources is the harder part.". Providing an example of a business problem that has been solved with technology, Mr Chan describes how the company has implemented mobile digital platforms to improve traceability from farm outputs and to bring data to the hands of farmers.

The magnitude of the problem to be solved by the adoption of technology is another important consideration. "We look to adopt and integrate those technologies that will help address the big needs and challenges that the company faces, such as those related to supply chain continuity and resilience, capacity enhancement of manufacturing sites, increasing return on investment in marketing campaigns," notes Anna Farberov, General Manager at PepsiCo Labs.

The technology's economic benefits are also critical: 79% of the respondents surveyed by Economist Impact highlighted that improving business operations such as cost savings is an important factor behind decisions to adopt technology. "Typically, for a company to adopt an emerging technology, the technology should either reduce the costs of operation or increase revenue for the business," notes Vishal Vijay, Director of Strategic Investments at Agrocorp. For example, smart farming techniques, such as through utilising IoT sensors or drones, enable businesses to collect data, reduce operational costs and improve resource efficiency (such as optimising labour productivity and precision farming).[77] Drones may apply pesticides and fertilisers to a rice field in about 15 minutes, while the same task would typically take more than an hour by hand, optimising and reducing the cost of farm labour.[78] While smart farming is broader and involves the use of data to drive efficiency across farm operations, precision farming focuses on leveraging technologies for on-field optimisation—which helps with cost saving on farm inputs. By using technologies like IoT sensors and drones to collect and monitor data on soil variations and individual plant needs, and big data analytics to generate intelligence to guide on-farm activities, businesses can optimise fertiliser use, resulting in fertiliser cost reduction, and a reduced environmental impact.[79] Further, IoT sensors can reduce water consumption on farms by 30%.[80] According to the American Farm Bureau, precision farming technologies can reduce costs by 15% and increase crop yield by 13%.[81]

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While global interest in smart farming technologies is increasing, their widespread deployment will likely remain a challenge due to a lack of affordability. Smart farming tools such as drones, satellite imaging devices and IoT sensors are expensive and remain unaffordable for small farmers in developed regions and a majority of farmers in emerging economies.[82] In addition to high initial investment, the use of such emerging technologies and tools requires a skilled workforce, which will remain a challenge for the adoption of these technologies among small-scale farmers for the foreseeable future.[83]

Companies are also deploying emerging technologies for improved employee safety as employees often engage in repetitive tasks and can be exposed to injury in large-scale food processing and packaging operations.[84] Advances in automation and robotics are making technology a viable solution to replace humans in conducting dangerous tasks, such as in meat cutting and processing.[85]

Legacy business models can be a barrier to technology adoption—running pilots to test viability and scalability can help

In large companies, adoption of emerging technologies may require a change in the business model.[86] For instance, decision-making can often mean going through rigid processes, requiring multiple levels of approvals and carefully planned yearly budgets. "A lot of planning is involved with regard to innovation—it takes time, effort and managing governance for innovation to happen," explains an industry expert from a large agri-food company. "One of the big problems is around consensus building, getting everyone aligned before moving along that path," they add In Economist Impact's survey, 13% of respondents highlighted "organisational inertia" as a bottleneck for adopting emerging technologies.

Kerstin Burseg, Programme Manager for Innovation at EIT Food,[87] offers some advice for innovation at large companies. To adopt technology more effectively, corporations may look at how startups work for some interesting lessons. "Big companies should have the willingness to give up some of the control in order to allow creativity and innovation to grow," she states. Anna Farberov highlights how PepsiCo is expediting the innovation process, particularly around working with startups, by "designing a fast-track process for each corporate function". She explains, "We have developed playbooks to streamline decision-making processes and simplify the engagement with corporate functions when working with a startup. For example, a standard security assessment process can be very complex in big companies like PepsiCo. When collaborating with startups for pilots, we have developed a light version of the security assessment because, for the pilot, the startups don't need to integrate into our systems. If they do integrate with us, we do a full-blown assessment but, before that, we need to do a pilot to see if there is even a business case."

Corteva Agriscience follows a similar approach whereby it uses R&D labs to test and pilot new ideas. "Within our R&D division, we have the machine that's built to discover, develop and commercialise products, but we also have a part where new ideas can come in: you can incubate them for a year to understand how the technology would add value, and if there is a business case to it," notes Wendy Srnic, Vice President, Seeds R&D, Corteva Agriscience. "We have forums, on a quarterly basis to

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annual basis, to discuss new technologies and what they mean to us, and to decide what we want to do in those spaces."

The adoption of emerging technologies also needs to consider the skills and learning curves of staff. "One thing that many of us actually miss, when we start implementing the technologies, is the learning agility of our people: people who are going to operate these new technologies are not college graduates, these are people who have run operations for decades," notes a global supply chain expert from a leading multinational company in the consumer packaged goods space. "Once you want to infuse any amount of visualisation or technology, I think the biggest challenge is to really have that mindset that this can work." Firms are increasingly facing the challenge of attracting new talent with digital expertise as a way to integrate technology in different parts of the business: 15% of respondents in the Economist Impact survey pointed to "lack of in-house talent" as a challenge for technology adoption, and in Singapore and the US, the share was around 20%. Some companies are making structural changes at the top. For example, the position of the chief digital officer (CDO), who supports management in formulating and executing a dedicated digital transformation strategy, is becoming more relevant.[88]

Consumer demand is influencing business strategy—scalability, high initial investments and funding are challenges

Consumer demand for knowing more about the food products they are buying, the origin of these products, and their impact on climate, is driving business strategies. "There is a huge discussion about climate change and its impact and how the world should face this issue, including the impact of the meat industry," notes Ido Yosovzon, AgriFoodTech Sector Lead at Startup Nation Central. "Consumers demand food products with lower negative impact on the environment, the corporate world needs to translate these demands." Some of these issues can be better managed through improved monitoring or tracking systems in the agri-food supply chain.[89] Traceability is focused on the implementation of safety- and quality-monitoring systems[90] and is becoming a key topic in the agri-food sector in building public trust in the food system, in addition to the business case for its use discussed in Section 3.[91] "We have been experimenting with the use of blockchain to add more traceability for customers," notes Mr Vijay at Agrocorp. "For example, by including scannable QR codes on retail packs, consumers can obtain information about which farm, which part of the world, the product originated from."

While businesses are increasingly experimenting with blockchain for better traceability, the technology faces challenges related to cost and infrastructure requirements. Implementing a new blockchain-enabled traceability infrastructure can be a huge and expensive undertaking for an organisation with limited resources.[92] The initial set-up and maintenance costs associated with blockchain require significant capital investment, putting firms with limited financial resources at a competitive disadvantage.[93] Many blockchain projects remain in the pilot stage as companies may be hesitant to adopt and use the technology due to a lack of experience. Technical issues in scaling these projects up include integration of legacy data or interconnection with existing IT infrastructure or other blockchains.[94] Blockchain adoption also requires highly

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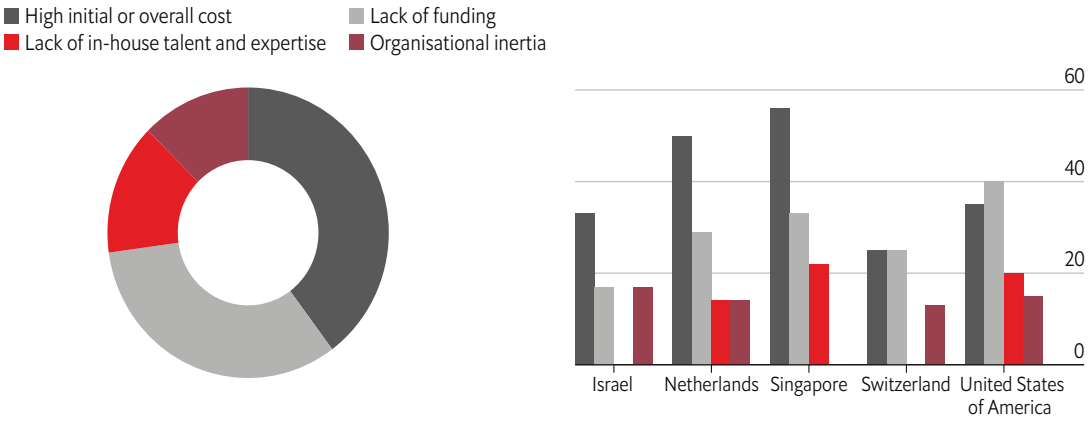
skilled internal manpower and employees may be unfamiliar with the functioning and maintenance of the technology.[95] According to one study, of 2m software developers in the US, only 5,000 were estimated to have skills needed to work with blockchain.[96] Adoption at a large scale would require training of all staff and not just the IT or operations team, which can be another challenge for companies.[97]

Figure 7: Business bottlenecks for technology adoption

Which of the following are some of the biggest bottlenecks in adopting emerging technologies in your sector? (Total and country results) (%)



Source: Economist Impact survey.

Organisations also have to support other stakeholders in their supply chain to overcome inertia in using blockchain and change their ways of operation. "In using blockchain to provide traceability information to our customers, we need to speak to the farmers that we buy our products from, and get them to directly upload information on the information sharing platform," notes Mr Vijay at Agrocorp. "That takes significant effort, as trying to convince farmers to adopt a technology can be difficult." Furthermore, it needs to be an entire supply chain effort. Adoption of blockchain by only select players in the supply chain is likely to generate only minimal cost benefits, and can result in an additional cost burden for those who adopt the new infrastructure while also needing to maintain fully operational traditional processes.[98]

In other fields like alternative proteins, years of R&D may be needed to achieve large scalability. "Probably the biggest challenge is investing in the infrastructure to support large-scale protein separation: a capital-intensive process that takes a long time to complete," notes Josh Tetrick, referring to the Just Egg division at Eat Just. "The nascent status of the alternative proteins sector makes the engineering of the infrastructure required to support the sector even more challenging." This struggle of alternative protein companies with scalability requires building more production facilities to improve accessibility and help companies focus their capital more effectively.[99]

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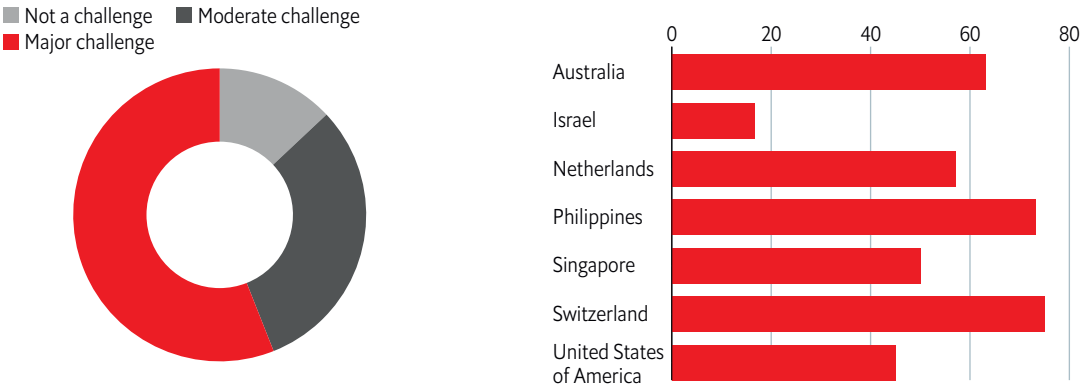
External factors: Regulation and consumer attitudes

External factors like the regulatory environment, intellectual property (IP) laws and their enforcement, and consumer attitudes can have a notable impact on technology adoption decisions: 75% of respondents in the Economist Impact survey consider a "favourable regulatory environment" an important or very important factor in determining innovation decisions. In addition, 81% of respondents consider consumer preferences, such as demand for alternative meat products, an important or very important factor in considering technology adoption.

Figure 8: Government regulation as a challenge for technology adoption

Over the next five years, do you anticipate government regulation as a major challenge for technological adoption in the agriculture and food sector?
(%)



Source: Economist Impact survey.

Effective regulation and intellectual property rights implementation can accelerate agri-food innovation

Regulations can drive innovation by creating incentives for efficiency. For instance, the 2009 US regulation making country of origin labelling (COOL) mandatory for meat products drove meat producers to develop innovative gene-marking techniques to improve traceability in livestock processing, as a way to minimise the cost of complying with the regulation in the long run.[100] In Economist Impact's survey, 55% of business leaders in the US rated favourable government regulation as a "very important" factor influencing organisations' decisions on the adoption of emerging technologies. Israel also offers some lessons in creating a supportive regulatory environment for innovators. Government regulatory bodies in the country hold regular consultations with startups to better understand the benefits, and use cases and challenges related to the development of emerging technologies, which ultimately supports the creation of appropriate regulatory guidelines that promote further innovation.[101]

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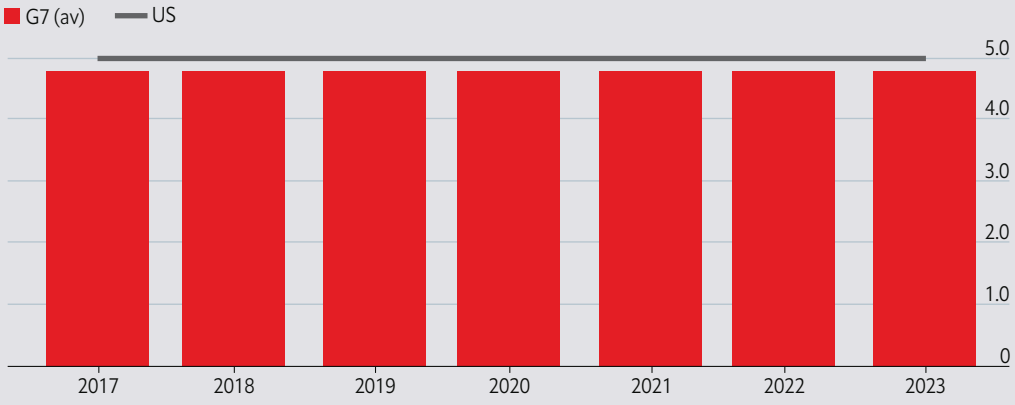
Protecting IP rights and assets is essential to fostering and rewarding innovation. Instruments such as trademarks, licences or patents allow innovators exclusive rights to benefit from an innovation. In this area, Israel is also an innovator—for instance, quasi-IP (IP that fails to secure protection within the traditional framework of IP rights and regulations) is protected from misappropriation under the Law of Unjust Enrichment.[102] In the US, strong IP rights, protection and enforcement drive investment in innovation and product development. IP-intensive industries account for 38% of the country's GDP.[103]

Enabling IP systems is driving agri-food innovation in the US

The US is a global leader in protecting IP that prevents innovators from losing out on the returns on their investments.[104] Sweeping reforms to the US patent system were made in 2012 and 2013 regarding the provisions of the Leahy-Smith America Invents Act (AIA). The legislation overhauled entitlement rights to favour the first inventor to file a patent application, rather than the first inventor to claim the subject matter. This update encourages innovators to become proactive about filing for patents and protecting their discoveries.[105] Figure 9 below on the level of IP protection shows that the US consistently performs better than the average of the G7 countries. "From the time you file a patent [in the US], you have exclusivity on that invention for a number of years, so that you can extract the value from that invention, and that's an incentive for people to innovate," notes Wendy Srnic at Corteva Agriscience. "And if they can improve that through that time, and get more IP on that space, they can continue there: that is a business, and so it just fuels more innovation."

However, IP rights are a matter of national jurisdiction, which means that if a company that has obtained a patent in the US wants to expand its operations to another country, it would have to file another application for IP rights protection there, and the strength of IP enforcement varies across countries. "We have decided not to do business in certain countries because it's so damaging where an invention is taken, and it's then found in many other countries," notes Ms Srnic. "So, very solid IP rights enforcement is key and in the countries that have it, we can bring brand new innovation that's going to really improve production."

Figure 9: Protection of intellectual property in the US versus the G7 average
(score; 5=high)



Source: EIU.

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Genetically modified crops face a highly varied regulatory environment

Agri-biotechnology, which involves complex technologies and techniques, is one area that provokes conflicting stakeholder views. New forms of plant and animal biotechnology, such as DNA sequencing, mutagenesis and genome-editing in particular, are areas that drive a great deal of public scrutiny. The area of GM foods is one where a sensitive debate is ongoing, with differences in consumer attitudes across regions. Even though scientific evidence has pointed to the safety of GM foods,[106] there are concerns around health and environmental risks. According to the World Health Organisation, GM food safety should be assessed on a case-by-case basis.[107]

The EU's strict regulatory framework for GM crops is influenced by a history of food safety scandals in the 1990s. Food safety crises, like Salmonella outbreaks and proliferation of dioxins, undermine consumer confidence in the food production and distribution system. There is also an ongoing debate around genetically-modified food. While scientific studies have identified genetically modified foods as safe for consumption,[108] opponents argue that there is still no clear conclusion about genetically modified crops, and genetic insertion could increase the formerly non-toxic elements in the plant.[109] In this environment of febrile debate,[110] genetically modified organisms (GMOs) are strictly regulated in the EU, with requirements for risk assessment, traceability and labelling.[111] Gaining regulatory approval to import a GM crop into the EU takes about six years on average, and longer when it is grown domestically.[112] The Economist Impact survey indicates that a larger share of businesses anticipate government regulation to be a major challenge to technological adoption in the agriculture and food sector in Switzerland (75%) and the Netherlands (57.1%), compared to the US (45%), over the next five years.

Low consumer acceptance in Europe[113] also drives limited cultivation,[114] with consumers far less likely to eat beef that comes from cattle fed on GM crops.[115] The EU further mandates that genome-edited crops should be treated as GMOs. Observers have called the legal framework for genome-edited crops in the EU not "fit for purpose", given that genome-editing involves altering the genes that already exist within the crop, as opposed to genetic modification, which involves inserting genes from other organisms (usually bacteria) into the crop's genome.[116] Many believe that newer gene-editing techniques should be assessed differently from GMOs and that the possibilities they bring for agricultural innovations should also be considered.[117] In April 2021 the European Commission launched a review of its rules on GMOs, which may be the starting point for further regulatory developments in this field.[118]

Given the global reach of the agri-food supply chain, the lack of regulatory support for GM crops in one market can act as a disincentive for producing those crops in other countries, and for exporting. In the US, for instance, while biotechnology regulations are relatively permissive, farmers often avoid growing GM crops such as wheat, rice and potatoes, fearing their commercial rejection in regions like the EU, where GM crops face stricter regulation.[119] Highlighting the potential impact of differences in global regulations on technology adoption, Wendy Srnic from Corteva Agriscience notes, "Without the assurance that we can develop

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a product using a new technology that will be approved globally, we are less likely to invest in its development. Likewise, growers and downstream grain handlers aren't going to take that risk, because they may not be able to sell their product that they've grown or purchased from that seed, or technology." Ms Srnic further observes, "Also, as the grain produced in the US or in Brazil moves all around the world, to get biotechnology traits approved you need regulatory approval from all of those countries, where they may be importing that grain (import approvals), and those global regulatory bodies are not usually coordinated on the requirements and the timelines."

Consumption of GM foods in the US is more prevalent than most other countries, and is a significant driver of the growth of the agri-biotechnology sector, globally.[120] However, in the US, despite widespread consumption of GM foods, consumer awareness about them remains paradoxically low. A study conducted by the Pew Research Center in 2016 revealed that over 60% of Americans had insufficient or zero knowledge about GM crops.[121]

Similarly, in Israel, much of the population does not have a strong opinion on the use of genetically engineered (GE) crops. While there are no restrictions on the use of imported GE commodities and derivatives in Israel, the current regulations do not permit the production of GE crops for commercial purposes, which can be grown only for research and experimentation.[122] In contrast, there is considerable consumer scepticism about GM foods in Singapore. A recent survey revealed that, of 1,000 respondents, nearly one-third found GM foods unappealing, over a third were neutral, and the remaining respondents welcomed them.[123] However, despite widespread consumer hesitancy towards GM foods, residents may not be aware of consuming food products derived from GM crops since labelling of GM food products and ingredients is not yet mandatory in Singapore.[124] Instead, food products for sale can be voluntarily labelled as "GM" or "non-GM", as long as the information is factual and not misleading.[125] Additionally, while there is no commercial production of GE food products in Singapore, the country is a large importer of processed food products, many of which (eg, corn syrup and soybean oil) may have been derived from GM crops.

Alternative proteins are seeing more acceptance in some countries

The alternative proteins field is proving increasingly popular in the context of sustainability concerns. This could show that there is more openness from consumers around certain innovations and these experiences could bring lessons to the whole industry on how to build trust with the public.[126]

Covid-19 has accelerated the concern around food safety and hygiene in the agri-food industry.[127] This trend may well give the alternative protein market a push. "We've seen a lot of demand for our protein that we're manufacturing in our plant in Canada, as well as increasing demand for our plant-based brand on the back of covid-19," notes Mr Vijay at Agrocorp. "The last few epidemics have been associated with the animal industry. So I think that realisation has allowed much more consumer acceptance and awareness for the benefit of plant-based food as well." Israel and Singapore are markets where new consumer trends are clearly evidenced. Data collected from brick-and-mortar stores in Israel highlights that growth of sales of substitutes

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for meat, milk and other dairy products were 13 times higher than growth of sales of animal-based protein products in 2020.[128] Similarly in Singapore, 2021 data from an app which helps users find sustainable food options suggested that consumers' interest in plant-based pork and chicken products increased sevenfold since 2019.[129] These demographic aspects play a part in innovations in places like Israel and Singapore. "We'd like to launch in places that have consumers who have an interest in eating healthier and are open to eating foods that are also a bit better for the planet," notes Mr Tetrick of Eat Just. "They tend to be more urban, a bit higher-income, more likely to be college-educated, and female."

Singapore is the first country to approve lab-grown meat

Economist Impact's survey on agri-food innovation shows that only 5.6% of businesses consider government regulations as an "extremely major challenge" for technological adoption in Singapore—much less than most other countries included in the survey. Following reorganisation in 2019 and 2020, a new food regulatory framework was launched in Singapore, which simplifies the patent-approval process and accelerates it by up to six months.[130] The new framework allows businesses to bring their innovations to the market expeditiously without compromising legal protection.[131] It is expected to increase global corporate investment in Singapore, as market access is a significant growth factor for frontier technologies. Owing to these factors, in 2020 Singapore became the first country to approve the sale of lab-grown chicken meat.

While most countries are yet to develop clear regulatory pathways for the production and commercialisation of lab-grown meat, and long regulatory approval processes inhibit the growth of the sector—for example, in the EU[132]—studies show that lab-grown meat could have significant environmental benefits. Scientific estimates suggest that lab-grown meat production could involve up to 96% fewer global greenhouse gas (GHG) emissions, 98% less land use and up to half as much energy, compared to animal meat production.[133] According to the UN Food and Agriculture Organisation (FAO), 14.5% of global anthropogenic GHG emissions come from livestock rearing.[134] Lab-grown chicken meat is growing in popularity in Singapore as an alternative to conventional animal meat. A recent survey of consumers dining at "1880"—the world's first restaurant to serve lab-grown chicken, located in Singapore—showed that 88% of consumers in the country are open to substituting conventional chicken consumption with cultured chicken.[135] Another survey, with an ethnically diverse sample size of 850 consumers in Singapore, highlighted that 78% of respondents were willing to try cell-based seafood options after being shown a simple infographic explaining the concept of the novel alternative protein.[136]

In addition to a favourable regulatory environment, ongoing efforts to develop a "regulatory sandbox" within the Agri-food Innovation Park—which will allow innovators to test new products and technologies in a controlled regulatory environment—are likely to further encourage agri-food innovation, demonstrating that the country is open to supporting other developments in the agri-food space. This space for experimentation may allow for quicker review and reform of existing regulations by the government.[137]

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While there is a segment of society that is more accepting of alternative proteins, these meat alternatives continue to face consumer hesitation globally. Research studies have found that urban, rich and well-educated consumers in China and India are much more likely to purchase cultured meat and plant-based meat products than US consumers. A survey from Germany highlights that while participants had positive associations towards meat, they viewed alternative meat products negatively, using terms like "unnecessary", "do not eat" and "does not taste good" in relation to meat alternatives.[138] In contrast, a study from Switzerland found that most consumers are positive or neutral about alternative proteins.[139] Consumer acceptance also varies according to the type of alternative protein. While plant-based meat and pulses are more accepted than insects and cultured meat, consumers who eat a relatively high share of meat as a part of their diet were more open to the idea of cultured meat than plant-based alternatives.[140]

Josh Tetrick from Eat Just highlights the challenges in persuading customers about the benefits of the alternative protein products. "The best way to change consumer behaviour is by putting the product in front of them; this will show them what the product is, that it tastes good and is better for their lives," he notes. Further, attitudes towards innovative food products may vary across generations. "Generally, the younger are more likely to be open," he adds.

Transparency, education and dialogue will be important tools for the agriculture and food sector to build public trust around innovations. Initiatives to this end include "Food Unfolded" by EIT Food, a digital platform for sharing with the public science-based knowledge about the safety and benefits of using emerging technologies for agri-food innovation.[141] Lack of familiarity and awareness about health and environmental benefits of alternative proteins is cited as a common barrier to consumer acceptance of these products. Building public trust for these products and educating people about their benefits will likely increase acceptance.[142]

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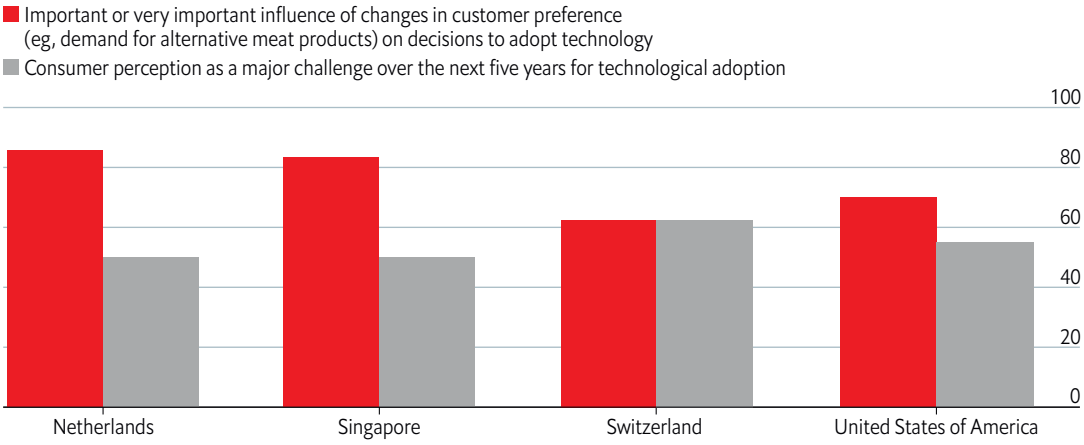
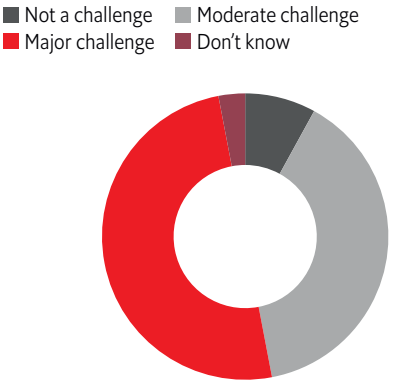
Figure 10: Consumer preferences/perceptions act both as drivers for and challenges to technology adoption

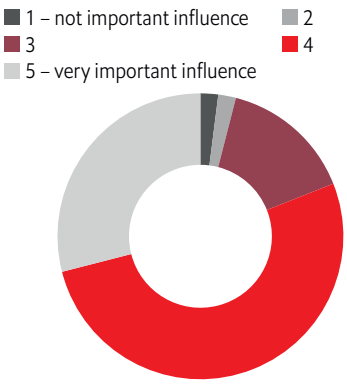
Do changes in customer preferences (eg, demand for alternative meat products) have an important or very important influence on decisions to adopt technology? Over the next five years, do you anticipate consumer per ception as a major challenge for technological adoption in theagriculture and food sector? (%)



Consumer perception as a challenge for technology adoption



Changes in customer preferences (eg, demand for alternative meat products



Source: Economist Impact survey.

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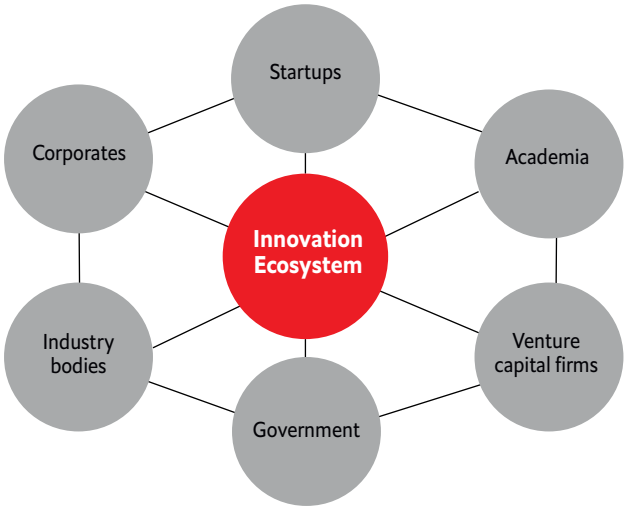
Stakeholder ecosystem analysis

Businesses don't innovate in silos. The agri-food innovation ecosystem consists of multiple stakeholders working together in distinct but important roles in enabling the development, promotion and adoption of emerging technologies in the agri-food sector. Various stakeholder dynamics need to be explored to examine the drivers and challenges that lead to a successful stakeholder ecosystem.

Figure 11: Building blocks of an effective innovation ecosystem



Pathways to adoption of emerging technologies

While large companies' in-house talent, skills and capabilities are critical for developing and implementing R&D projects,[143] they recognise that not all good ideas will come from within the organisation.[144] A global supply chain expert from a leading multinational company in the consumer packaged goods space highlights the importance of collaboration: "We are taking a hybrid approach, and not

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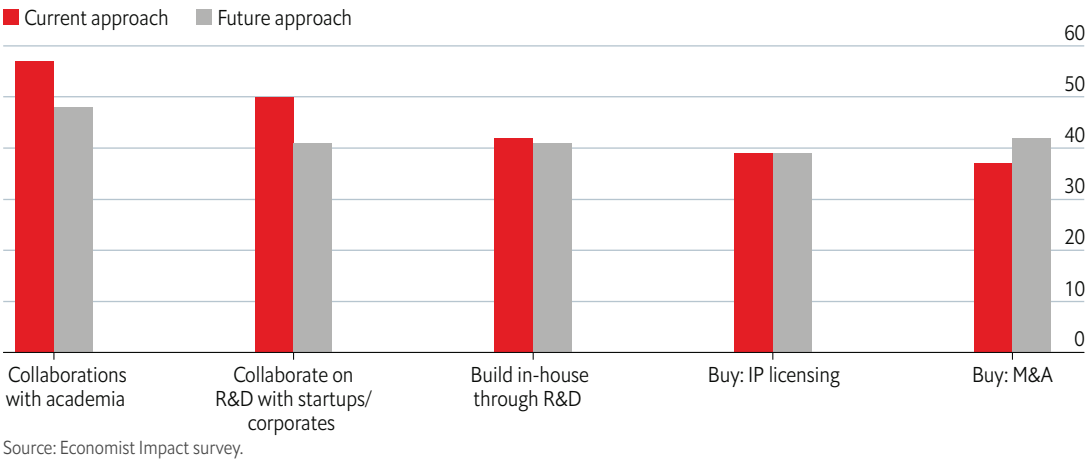
really getting fixated about developing everything in house ... We are using our in-house capabilities to customise an available solution to fit our ecosystem and not really developing something from scratch."

In the Economist Impact survey, collaboration with the academic sector is the most common approach to adopting emerging technologies, with 57% of respondents highlighting collaborations with academia (such as institutes of higher learning and research institutes) as a common approach to gaining access to emerging technologies. Next is collaboration with startups: 50% of the respondents in the survey consider partnering with startups a common way to facilitate access to emerging technologies for agri-food innovation. Given the growing complexity of the global food system and an urgent need to respond to disruptions—such as those caused by the covid-19 pandemic—corporations are increasingly looking to partner with startups to speed up innovation.[145]

Economist Impact's survey suggests that mergers and acquisitions (M&A) and IP licensing are currently less popular approaches for respondents to gain access to emerging technologies. However, M&A is the only approach that is likely to witness increased adoption in future, according to the survey. Market volatility associated with the pandemic contributed to a slowdown in M&A activity in the technology sector. Global M&A transactions in the food and beverage industry decreased sharply from a monthly average of 34 in Q1 in 2020 to a monthly average of 16 for April and May 2020.[146] However, M&A activity is likely to rebound as economic stability improves.[147] There is confidence among industry stakeholders in a strong market recovery, which is likely to increase appetite for M&A.[148] Moreover, as a growing number of young companies are reaching maturity in the agri-food space, M&A may become more common (as opposed to corporate buyouts of early-stage startups).[149]

The corporate sector's two most common approaches to technology adoption—academic collaborations and startups—are examined in more detail below.

Figure 12: Approaches for organisations to gain access to emerging technologies
What is your organisation's current most common and future most likely approach to gain access to emerging technologies? (%)



Source: Economist Impact survey.

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Universities, institutes of higher learning and academic collaborations provide a testing ground for new ideas and a source for talent

By partnering with academic centres, corporations can leverage high-tech research capabilities of universities, which helps reduce the cost of research (as it would likely be higher if undertaken in-house), innovation and product development.[150] For example, in the US, there are facilities for nanotechnology research located in universities and national labs which are funded jointly by the government, universities and industry. These are open to industry partners seeking access to this emerging technology. Eventually, such emerging technologies and cutting-edge equipment can mature into standard resources for the industry.[151]

For companies, universities and institutes of higher learning can be a source of cutting-edge knowledge for novel ideas and new product development.[152] Staying aligned with early-stage research enables companies to identify the investment opportunities with the greatest potential, helping them to stay ahead in a competitive market.[153] Nestlé, for example, partners with the Center for Microbiome Innovation at the University of California San Diego to understand the microbiome's impact on human health and accelerate the development of innovative nutritional solutions.[154] Additionally, academia can be a source of talent identification and acquisition for companies.[155] Companies often do not have the time to incubate ideas themselves, necessitating the acquisition of new talent—such as recent graduates or researchers at universities—with a finger on the pulse of emerging markets.[156] Another approach to leveraging the capabilities of the academic sector in industry is the licensing of new technologies. According to Dorit Rozner, Chief Technology Officer at The Kitchen FoodTech Hub, this is the experience of The Kitchen Hub, which engages with academia to license technologies developed at universities. Companies can then be built from scratch to adopt and implement that technology. Universities are also increasingly looking towards industry to fill funding gaps for research. By partnering with companies, academic institutions can obtain industry feedback, which can contribute to the success of their own innovation programmes.[157]

Companies also consider partnering with universities to test and affirm the viability of a new technology. For example, Wendy Srnic from Corteva Agriscience notes that, "As our focus is on product development, nascent technology is a little too raw for a company our size. So we generally let the university incubate it for a while, and then once startups start developing that technology further, and there is proof of concept, it triggers us to look at how we could fit that into our product development." In cases where universities may not serve as sources of technology or talent, they can serve as platforms for agri-food companies to test new products and technologies. "Many times we work with universities downstream as we're getting our products closer to development, because the universities can test the products and help us understand their market potential," notes Ms Srnic. "In that sense, universities function more like influencers or validators of the kinds of products we're bringing out, rather than as the source of the nascent technology."

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Matching the agility of startups with corporate scale

"Startups are leading the unprecedented pace of change in innovation," according to Anna Farberov from PepsiCo Labs. "Once you acknowledge that, then it's not about if, it's about how. In order not to be left behind you need to find the most effective way to collaborate with startups." Through collaborations, corporations can leverage the ability of startups to develop new technologies. "If there's a big company that's focused on one thing, and they are interested in exploring another domain without making huge investments, it makes sense for them to work with a startup or a smaller company," notes Daniel Koppel, co-founder and CEO of Prospera Technologies. "The big corporate brings the distribution, the brand, the know-how, and the startup brings agility, technology, and innovation." Large companies can provide financing, industry expertise and network access to support startups in scaling up.[158] Well-established agriculture and food companies are also increasingly collaborating with startups to maintain a competitive advantage in this fast-growing sector.[159]

The interest in collaborating with startups is even mobilising large corporations to partner with their peers. An interesting example is that of Givaudan, which launched an innovation platform, MISTA, with Danone, Mars and Ingredion in San Francisco.[160] Benefiting from its proximity to Silicon Valley, MISTA brings startups together in a physical space to develop and pilot their products, working on the future of food.[161]

Collaboration is not without challenges, with the risk of misalignment in terms of how startups and corporations operate. "Startups move fast, while big companies could take 9–12 months between early conversations and signing a deal", notes Jonathan Chan at Cargill. "Most startups actually run out of funds before they are able to sign that deal itself." New startups may still not have the solidity necessary to deal with lengthy and complex operations with corporate partners. An industry expert from a large supply chain company elaborates on the challenges in working with a startup specifically in the area of supply chains: "One of the challenges for a startup with our type of operation is we can easily crush them with our size and complexity. It's not like we don't work with startups, but we probably prefer more mature, easy-to-implement technologies." Other industry experts also echo the preference to work with technologies that are relatively mature and at later financing stages.

How can startups prepare for a successful collaboration with corporations? As pointed out in Section 3, creating an easy, fast and straightforward collaboration process for running pilots could be a key step. Big companies can prepare playbooks, shorten approval processes and use a dedicated space to test the potential viability of a collaboration and the technology through these pilots.[162] If the pilot does prove successful, it would make a strong case for a next step in the collaboration. The right corporate partners can help startups to scale their missions. For Ms Farberov, supporting startups as they bring their products to market is one of their goals: "It's not the question if some things in the pilot will go off-track, it is what you do when they do, and how do you as a team (startups and corporates) move past that

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and work towards solving the problem.". Ms Rozner from The Kitchen Hub highlights the importance of the team in a startup: "In order to work successfully with corporates, the team needs to be professional, patient, responsible, trustworthy and transparent.".

For startups, it can be challenging to find the right contacts in large corporations.[163] Venture capitalists and venture capital firms play a key role here. Those that play an important role in funding startups also act as intermediaries, providing vetting of startups for some corporations. "We start with 200–300 startups that are relevant that are being sent to us by the venture capital firms. The long list is then filtered by PepsiCo experts," notes Ms Farberov in describing the process of identifying suitable startups to work with.

Government support is key to the innovation ecosystem

Governments are well placed to provide strategic guidance on research and innovation and provide funding to research institutions.[164] Sustained government support contributes to the growth of the agritech sector, as seen in the case of the US and Israel—countries that are leading agritech innovation globally.[165] "The government has a crucial role in bringing funds, but also in establishing the infrastructure and targeting the spotlight on areas with the highest growth potential," notes Ido Yosovzon at Startup Nation Central in Israel.

In supporting innovation, the Israeli government provides risk-free funding to startups at the early stages, supporting their maturity and enabling other stakeholders such as venture capitalists to step in at the later, less risky, stages. "You can have an idea, but no one will invest in such an early stage, it's too high-risk," notes Ms Rozner. "So the government has all kinds of grants to support entrepreneurs and help them to do their first proof of concept." (See Box 3 below for further details). Israel also invests significantly in R&D, allocating 17% of its total agricultural budget for this purpose.[166] In the US, the National Institute of Food and Agriculture conducts R&D in physical sciences, supports the development of agricultural devices, promotes applied research to assess economical ways of employing emerging technologies, and provides assistance to farmers on using those technologies.[167] Furthermore, the US Department of Agriculture (USDA) recently announced the availability of grants worth US$4m to further support urban farming entrepreneurs and businesses looking to innovate.[168]

The EU has also developed policy initiatives that are likely to promote innovation in the agriculture and food sector, such as the Green Deal[169] and the Farm to Fork Strategy.[170] Yet, according to Olaf van der Veen, Co-founder and CEO of Orbisk, it is not always easy to access funding for startups working in niche or novel areas, such as Orbisk's area of food sustainability. "It wasn't easy to secure funding in the early stages of our company, compared to other technologies, because although we are very profitable we are still a sustainability initiative," he explains.

In Singapore, there is growing collaboration between the government and research institutes like the Nanyang Technological University and Temasek Polytechnic, which has led to the establishment of a number

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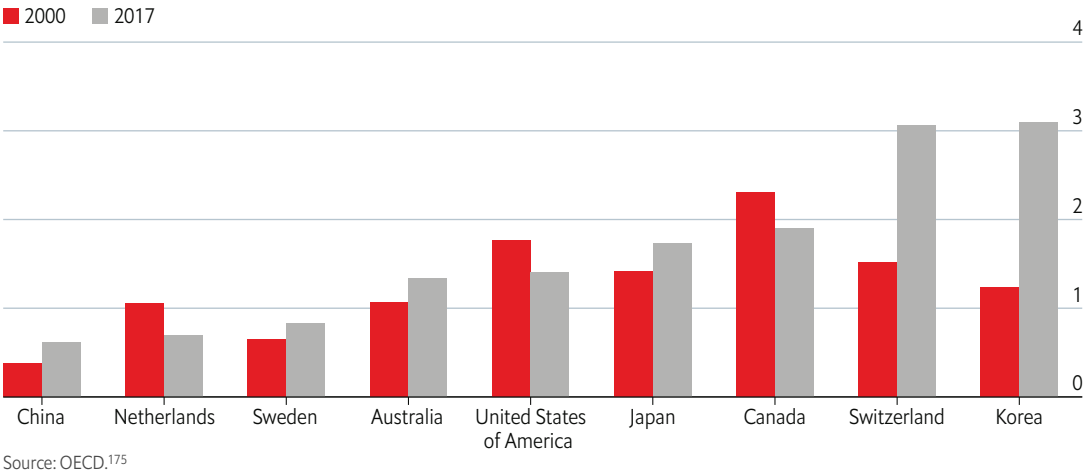
of innovation centres that focus on finding solutions for agricultural challenges. Some notable results of such collaborations include the successful breeding of freshwater tilapia fish in sea water without genetic modification, the production of "climate-proof" vegetables that require less light and yet have enhanced nutritional value, and a number of rice varieties that can withstand flood, drought and bacterial attack.[171]

Industry bodies, investors, accelerators and incubators as valuable intermediaries

In addition to the government, industry bodies, investors, accelerators and incubators play an important role in creating a successful innovation ecosystem. Accelerators offer startup capital, mentoring, access to companies, investors and press, shared space and alumni networks. At times, these accelerators act as "matchmakers", connecting startups and corporates.[172] Although both accelerators and incubators offer support and guidance to startups, incubators are typically targeted at companies at an earlier stage. Accelerators are targeted at existing companies that have an idea and a business model already in place but need help in propelling their business forward.[173] Industry bodies are another type of intermediary for innovation, working independently to support the development of a specific sector. "Access to market, inability to target the market needs, issues in access to funding, and incomplete knowledge of how to run a business are the key challenges in front of startups, and industry bodies can help address these concerns," notes Kerstin Burseg at EIT Food.[174]

Figure 13: Public R&D intensity on agricultural sciences, 2000 and 2017
Government budget allocations for R&D on agricultural sciences as a percentage of agricultural value added



Source: OECD.[175]

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Israel: An innovation ecosystem in action

Israel offers lessons in creating a thriving innovation ecosystem in the agri-food sector. The government's Yozma programme, launched in 1993, became a catalyst for the country's venture capital industry. Yozma began to invest in ten new venture capital funds for a 40% stake in the company to cover the initial risks faced by the industry. In addition, it attracted foreign investors by providing insurance coverage for up to 80% of the downside risk.[176] "In the beginning, when the risk was big, the Israeli government provided risk-free funding. The government supported the startup directly, at an early stage until the venture capitalists could come in," notes Anna Farberov of PepsiCo Labs. "This early-stage investing created a lot of early-stage companies that matured and created an active ecosystem that feeds itself." The government also backs the agritech industry by actively connecting different players in the ecosystem.[177] GrowingIL, a non-profit venture, is connecting different actors in Israeli agritech by organising events that address the ecosystem's unmet needs.[178]

Numerous other actors play a part in the success of this ecosystem, and their collaboration is key. "I think that the most important building blocks that we have are the ecosystem of entrepreneurs, investors and industry researchers, in addition to the government funding for accelerators," notes Dorit Rozner of The Kitchen FoodTech Hub. "And also the relationship between industry and academia is an important factor for innovation and new startups in foodtech."[179]

In Israel, the strong interlinkages between different players provide agility and enable a quick conversion of high-potential academic research into a market solution.[180] The innovation starts in the academic world, with a strong academia–business technology-transfer culture. For example, Yissum, a technology transfer organisation of the Hebrew University of Jerusalem, has developed expertise in commercialising university discoveries to the market[181] by connecting cutting-edge university research with a global community of entrepreneurs, investors and industry organisations.[182] According to Ido Yosovzon from Startup Nation Central, "In Israel, strong institutions with leading researchers are creating the scientific research that can then be commercialized through the university's technology transfer offices… We see a lot of companies that spin off from academic institutes and build successful commercial ventures based on scientific research that started in the universities."

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Key takeaways and future implications

Feeding the global population in the future will require a more efficient agriculture and food sector than the one we have today. Innovative technologies are offering possibilities that could help address the biggest challenges in the sector. Increasing the productivity of agricultural land and reducing food waste in the supply chain can help achieve food security. Novel food products can meet the rising demand for protein and supplement wider diets. Emerging technologies are at the core of these solutions. As highlighted in this report, while the sector is experimenting with and adopting these technologies, there are many barriers to innovation and adoption remains uneven. In the coming years, the stakeholders discussed in Section 5 will play a key role in creating a thriving ecosystem for innovation in the sector, for experimentation as well as wide-scale adoption.

Plant-based and cultured meat have the potential to become sustainable solutions for Asia's rising demand for meat. Regulatory approval and consumer acceptance will be key to success.

In Asia, population growth and rising incomes are expected to drive demand for protein—particularly animal-based protein like meat and dairy products. Meat and seafood consumption is estimated to rise by 78% between 2017 and 2050 in the region.[183] Meanwhile, South-east Asia is set to become the world's fastest-growing importer of soybean meal, a key ingredient of animal feed, by 2028.[184] Beef, a popular meat option in Asia, accounts for 41% of total GHG emissions caused by animal meat production.[185] Alternative proteins offer a sustainable way forward to manage the rising demand for meat. In Singapore, where consumers have had the opportunity to try lab-grown meat, acceptance seems relatively high. Sustainability is a key motivation for consumers to try alternative proteins like cell-based seafood.[186]

In Asia, while 13% of the population identified as vegan in 2020—much higher than in Europe (4%)—the growing demand for animal meat is likely to impede the growth of the plant-based proteins sector.[187] While these alternatives are seeing increasing consumer acceptance, research shows that a large number of consumers still do not prefer these products, primarily due to unfamiliarity with them. Educating consumers about the health, nutritional and environmental benefits

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of these products could change that.[188] Governments and civil society organisations can play a leading role in building trust and educating people about the benefits of these products.

Cultured meat continues to face regulatory barriers globally.[189] In the EU, it has been recognised as a way of achieving future food sustainability targets, yet gaining approval can take up to 18–24 months.[190, 191] In the US, multiple checks with regulators at different stages of production lengthen the process.[192] Israel is home to the world's first restaurant dedicated to cultured meat, although the meat cannot be sold yet since it is not yet regulated in the country. The restaurant hosts periodical test meals to generate customer feedback.[193]

In countries where alternative meat products do pass regulatory barriers, achieving scale in production will determine the success of these technologies. According to Josh Tetrick of Eat Just, "The biggest challenge is that the primary way of making it at scale is not available: you make meat in a bioreactor, which is an essential element in providing the environmental conditions for the growth of a culture,[194] and if you want to make millions of pounds of meat, you need 100,000-litre-plus bioreactors … But no company in the world currently makes those sets, that's the biggest limiting step." Scalable, cost-effective production will be needed for cultured meat to become a viable alternative to meat around the world.[195]

Collection, monitoring, and analysis of big data using technologies like IoT, drones and AI have many benefits, from improving farm productivity to reducing food waste.

Big data is enabling agricultural productivity, safety and efficiency.[196] Capabilities in data collection are growing through the use of specialised technology. "Data is going to enable newer, more efficient farming practices and will connect the agri-food ecosystem," notes Jonathan Chan from Cargill. Greater capabilities in data gathering, processing and analysis underpin the deployment of many emerging technologies in the agri-food space, and data will continue to be the driving force of innovation in the future. "The area of IoT and sensors enables the collection of data at a granular level that allows us to do all these things," adds Mr Chan.

"We are looking at how we can use imagery to translate what we're seeing in the field into data, using drones for gathering insight and data from what we're seeing in the field in a way that we could never do before," notes Wendy Srnic at Corteva Agriscience. Against the backdrop of these benefits, agricultural drones are expected to capture 80% of the commercial unmanned aerial vehicle market and have the potential to generate more than 100,000 jobs in the US.[197] In Japan, the government has unveiled a plan to promote the use of drones in agriculture to address future labour shortages as a result of an ageing population.[198] Cutting-edge technologies such as drones could attract younger workers back to farms.[199] In contrast, countries with a younger demographic might face resistance due to the technology's potential to replace human labour. Studies suggest that drones could replace over US$32bn of human labour in the agriculture sector alone.[200]

Achieving food security would require fixing the issue of food waste. Dutch startup Orbisk is using an AI-driven image-recognition technology to cut down food waste in the retail and restaurant sector. Its solution allows scanning images of all wasted food

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streams before being disposed of in order to collect data on the volumes and type of food waste produced. The data is intended to help restaurant owners and chefs understand their food waste and thereby improve their sustainability strategy.[201]

Accelerating such innovations to address food waste will require a supportive regulatory and policy environment. According to Economist Impact's Food Sustainability Index, among the G20 countries, Canada, Italy, Germany, Japan and the US are performing particularly well on indicators on food loss and waste as a result of dedicated policies and national legislation to reduce food waste. However, in many countries, measuring food loss or waste remains a challenge,[202] and a lack of concise data on food waste is a major cause for inaction.[203] The UNEP Food Waste Index notes that 75% of the global population resides in countries with some estimates for household food waste, but that proportion falls to 14% for retail waste.[204] Solutions such as satellite imagery and citizen-generated data are accelerating the speed of data collection on food waste and decreasing the associated collection costs.[205] Targeted policies will make a further business case for this market.

Food safety risks in the supply chain can be a source of disease. Creating a blockchain ecosystem, with easy adoption by all players, can improve food safety.

In Asia-Pacific, the covid-19 pandemic has accelerated the demand for safe and secure food.[206] A recent study showed that 73% of consumers in Asia are sceptical about the ability of existing food supply chains to prevent food contamination.[207] In the US, a 2018 E. coli outbreak linked to romaine lettuce spread across 22 states, revealing gaps in the system used to track food pathways.[208] Responding to these food safety concerns, agri-food companies are increasingly adopting emerging technologies like blockchain that can facilitate traceability and transparency along the supply chain.[209] Other tools include Radio Frequency Identification (RFID) tags and QR codes.[210]

Since an efficient tracking system requires the participation of all players along the value chain, there are challenges in achieving global adoption. Limited digital literacy and infrastructure constraints with respect to small and rural farmers will be key issues in addressing these challenges.[211] Ongoing efforts, such as through GS1, a global, not-for-profit organisation managing industry-driven data and information standards, would need a further push. Governments are also stepping up to the task of greater traceability and promoting the use of technology. Addressing the absence of a harmonised system of traceability from farm to fork, the US Food and Drug Administration has implemented a blueprint strategy that promotes the use of technologies like blockchain and IoT sensors for the implementation of advanced traceability systems to enable location tracking and identify the source of contaminated food.[212, 213] In 2021 Singapore launched the Future Ready Food Safety Hub (FRESH) with the aim of accelerating food safety research, supporting food science capabilities and enabling regulatory responsiveness to speed up the commercialisation of novel foods. The hub will also provide a platform to foster collaboration between regulators, public researchers and the industry on food safety R&D.[214]

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Personalised nutrition is gaining greater consumer attention, a trend accelerated by the covid-19 pandemic. Biotechnology, AI and 3D printing could enable effective responses to such trends.

The covid-19 pandemic has increased public awareness around "prevention" and "wellbeing" worldwide. Personalised and health-promoting nutrition solutions have experienced a boost in these times.[215] A 2020 global consumer survey showed that personalised nutrition is an important consideration for 64% of consumers when purchasing products.[216] After the pandemic, the global personalised nutrition market size is projected to grow at 15% year on year, from US$8.2bn in 2020 to $16.4bn by 2025.[217] According to Dorit Rozner of The Kitchen FoodTech Hub, "Consumers are becoming increasingly aware that gut health is related to various diseases, inflammation, brain health and the immune system. This is why we are seeing an increase in the demand for nutritious food and ingredients such as probiotics and prebiotic fibers that help increase the diversity of the microbiome in the gut, which helps to maintain a healthy gut. " Advanced supplements represent a promising area within the field of personalised nutrition. A 2020 report suggested that 67% consumers in the US were interested in customising their supplements based on DNA test results; however, privacy concerns around health data and the high cost of operating screening technologies are considered obstacles for the growth of this industry.[218]

Several emerging technologies enable personalised nutrition including biotechnology techniques like cell-culture, precision fermentation, AI and 3D printing. Cell-culture, which is used to produce cultivated meat, can fortify food with minerals and nutrients, making the end-product more valuable for the consumer.[219] "We will have cultivated meat products that contain less fat and no antibiotics; maybe we'll be able to control the iron," notes Ms Rozner. "We will have cultivated fish with no heavy metals like mercury, and we may be able to control the quantity of omega 3."

Mobile apps driven by AI use lifestyle and food data to create personalised diet plans for consumers. For example, AI algorithms developed by IBM Research recognise food items through images and help track nutritional intake more easily.[220]

Companies are also experimenting with 3D food printers to deliver food with personalised nutritional profiles to consumers. For example, Anrich3D, a Singapore-based 3D food-printing firm, is working to produce mathematically optimised meals with precise amounts of ingredients, tailored to consumers' specific needs. The variety of flavour profiles in Singapore, due to an ethnically diverse population and a general tendency towards healthier eating, are key considerations driving the company's decision to launch there. Singapore can also serve as a launchpad for technologies and businesses to expand into neighbouring markets.[221]

Limited resources are driving innovation in agricultural production. Resource-constrained countries are experimenting with vertical farming. Precision farming and agri-biotechnology could drive large-scale farm productivity.

If left unaddressed, agricultural production will continue to present a massive environmental challenge. In Economist Impact's survey, 77% of business leaders consider developing climate resilience, such as farming or

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production in drought conditions, an important factor influencing their decisions to adopt emerging technologies. According to Wendy Srnic of Corteva Agriscience, "Producing enough on the land that we currently have, without having to bring huge amounts of more land into production, is a major objective of the agri-food industry … Which means increasing land productivity through higher yields using genetics and technology to optimise how crops are grown through the season, preventing wasteful production."

Vertical farming can be an alternative. In densely populated countries like Singapore, vertical farms are considered ideal as they use limited space. In 2019, close to 15% of the total volume of leafy vegetables produced in Singapore came from urban farms.[222] The country currently has at least 25 vertical farms,[223] such as SkyGreens, which produces over 800 kilograms of vegetables daily.[224] However, high initial investments, high running costs and low profitability remain roadblocks for large-scale adoption of this technology. Studies reveal that the initial investment to cultivate a vertical farm is ten times that required by greenhouses.[225, 226] In the future, cheaper greener electricity could be key to the profitability of this technology.

Agri-biotechnology is another area of innovation that can support climate-resilient agricultural production. In 2019, researchers in Delaware achieved an increase of up to 10% in corn yields by modifying the gene that controls the crop's growth.[227] However, globally, views on GM crop uptake are likely to remain divided. While GM crops are widely used in the US and China,[228] consumers in the EU largely remain resistant to GM foods, citing health-related and environmental concerns.[229]

Regulatory barriers also inhibit the growth of the sector in the region. Given the significant impact of government regulations on GM food market dynamics, regulatory reform will drive the pace of innovation in this sector.

Precision farming is helping some farms improve agricultural productivity. It is estimated that if 15–25% of farms adopted precision agriculture, global yield could be increased by 10–15% by 2030, while GHG emissions and water use could be reduced by 10% and 20%, respectively.[230] Greater precision means water, fertiliser and other inputs can be reduced with no impact on yield.[231] Prospera is an Israeli startup deploying machine learning and computer vision to facilitate agricultural data collection in order to help farmers make informed decisions. Its co-founder and CEO, Daniel Koppel notes: "Think about all the decisions farmers need to make, from the moment they put their seeds in the ground all the way to when they harvest … We look at things like understanding the stress levels and health of a plant, and provide recommendations on irrigation, fertilisation, pests and nutrient deficiencies." Despite the visible success of the technology, there are challenges facing wide-scale adoption of the technology. In the US, large companies have started implementing this approach. However, adoption is lagging among small farms, which make up over 85% of all farms in the country.[232]

Emerging technologies offer possibilities to help address the many challenges surrounding food security, sustainability and safety. Technologies can help enhance the productivity of agricultural land, improve crop resilience and reduce food waste in the supply chain. Novel food products can meet the rising demand from consumers for

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meat in a sustainable manner. There remain barriers to innovation, and adoption is uneven. Organisational challenges include legacy organisational mindsets and a lack of funding. External factors such as a lack of government support or consumer acceptance are also important influencing factors. Addressing the growing demand for food will require wide-scale adoption of emerging technologies, supported by an ecosystem that promotes innovation in the agriculture and food sector to create a more resilient and sustainable food future.

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Appendix 1: Methodology

This report is the product of a primary research survey of 100 business leaders from agri-food companies, interviews with industry experts in the sector, and an extensive literature review, conducted by Economist Impact.

Primary research survey: Economist Impact conducted a primary research survey of 100 respondents covering small, medium and large corporates (with over 100 employees) in the three agri-food sub-sectors of agritech, agri-food supply chain, and foodtech. The survey gauged the perspectives of business decision-makers on the adoption of emerging technologies, drivers and challenges behind adoption, and the prospects of these technologies in the sector. The survey covered seven key markets: Australia (19%), Israel (6%), the Philippines (15%), the Netherlands (14%), Switzerland (8%), Singapore (18%) and the United States (20%).

The following table presents an overview and composition of the sample size of the survey:

Sector/Sub-sector	Share of respondents
Agricultural and Farm Machinery	14%
Agricultural Products and Commodities	6%
Agricultural Technology	8%
Fertilisers and Agricultural Chemicals	7%
Fast-moving Consumer Goods (including consumer packaged goods and beverages)	12%
Food Processing	13%
Food Retail and Delivery Services	9%
Food Safety	8%
Next-generation Food & Drinks (for example, the development of alternative proteins)	4%
Restaurants and Hospitality	14%
Food Supply Chain and Logistics	5%

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Qualitative interview programme: Economist Impact interviewed 14 experts from across agri-food corporates, startups and industry bodies to draw key insights and reveal regional nuances on emerging technological trends. We would like to thank the following experts for their time and insights:

- Kerstin Burseg, Programme Manager for Innovation, EIT Food
- Jonathan Chan, Digital Advisor APAC, Cargill
- Sharon Devir, Co-founder & Chairman, SaliCrop
- Louis Dreyfus Company
- Anna Farberov, General Manager, PepsiCo Labs
- Daniel Koppel, Co-founder & CEO, Prospera Technologies
- Dorit Rozner, Chief Technology Officer, The Kitchen FoodTech Hub by Strauss Group
- David Sheldon, Global Supply Chain Development, Nestlé
- Wendy Srnic, Vice President, Seeds R&D, Corteva Agriscience
- Josh Tetrick, Co-founder and CEO, Eat Just
- Olaf van der Veen, Co-founder & CEO, Orbisk
- Vishal Vijay, Director of Strategic Investments, Agrocorp
- Ido Yosovzon, AgriFood-Tech Sector Lead, Startup Nation Central

Literature review: The analysis in this research was informed by an extensive literature review and media scan of global and regional sources to identify and examine technological trends in the three sub-sectors within agri-food—agritech, agri-food supply chain, and foodtech.

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Definitions of key terms, listed in alphabetical order:

Technology /Technique	Definition/Application	Source	Referred on page number
Agri-biotechnology	A range of tools, including traditional breeding techniques, that alter living organisms, or parts of organisms, to make or modify products, improve plants or animals, or develop microorganisms for specific agricultural uses.	USDA[240]	9
Agri-food supply chain	The agri-food supply chain sector encompasses the supply chain and logistics sector as well as the food safety and food-processing sectors, covering the entire flow of food products from the post-production to pre-consumption stage.	FAO[250]	11
Agritech	The application of technology to produce more with less, to make the farming process more efficient, from field monitoring to the food supply chain.	Investment Monitor[233]	9
Artificial intelligence (AI)	A constellation of many technologies working together to enable machines to sense, comprehend, act and learn with human-like levels of intelligence.	Accenture[251]	13
Automation	The process of human input being minimised by technology applications. This includes business process automation, IT automation, and personal applications such as home automation.	IBM[236]	9
Big data analytics	The process of uncovering trends, patterns and correlations in large amounts of raw data to help make data-informed decisions. These processes use familiar statistical analysis techniques—like clustering and regression—and apply them to more extensive datasets with the help of newer tools. Big data has one or more of the following characteristics: high volume, high velocity and high variety.	Tableau[237], IBM[238]	9
Bioreactor	A manufactured device in which a biological reaction is carried out. It is a closed system used for bioprocessing that supports the growth of cells or tissues. The process can be aerobic or anaerobic. Bacterial reactions generally take place in fermenters, whereas the growth of cells occurs in a bioreactor.	Spectac International[260]	35
Biotechnology	Technology that utilises biological systems, living organisms, or parts of these, to develop or create different products. Biotechnology covers many disciplines such as genetics, biochemistry and molecular biology.	Norwegian University of Science and Technology[239]	9
Blockchain	Blockchain facilitates the process of recording transactions and tracking assets in a business network whereby anything of value can be tracked and traded on a blockchain network, reducing risk and cutting costs for all involved.	IBM[252]	13
Cultured meat	Cultured or cultivated meat is genuine animal meat produced by cultivating animal cells. It is made of the same cell types arranged in the same or similar structure as animal tissues, thus replicating the sensory and nutritional profiles of conventional meat. This production method eliminates the need to raise and farm animals for food.	Good Food Institute[255]	16
DNA sequencing	A laboratory technique used to determine the exact sequence of bases (A, C, G, and T) in a DNA molecule. The DNA base sequence carries the information a cell needs to assemble protein and RNA molecules. DNA sequence information is important to scientists investigating the functions of genes.	National Human Genome Research Institute[258]	23
Drones	A drone, or unmanned aerial vehicle, typically refers to a pilotless aircraft that operates through a combination of technologies such as computer vision, AI and object avoidance technology.	CB Insights[248]	10

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Definitions of key terms, listed in alphabetical order:

Technology /Technique	Definition/Application	Source	Referred on page number
Fermentation	A process of using microorganisms to produce alternative proteins, taking three forms: traditional fermentation can be used to improve the flavour or functionality of plant ingredients through microbial anaerobic digestion; biomass fermentation uses the high-protein content and rapid growth of microorganisms to efficiently make large amounts of protein-rich food; precision fermentation uses microorganisms to produce specific functional ingredients. The microorganisms are programmed to be miniature production factories.	Good Food Institute[256]	16
Foodtech	An emerging, consumer-centric sector focused on the latter part of the supply chain. Foodtech covers sectors such as the development of next-generation food and drinks, kitchen and restaurant technology, food marketplaces and delivery, and surplus and waste management. The sector is "exploring how technology can be leveraged to create efficiency and sustainability in designing, producing, choosing, delivering and enjoying food".	Forward Fooding[253]	14
Gene editing	Genome editing is a method that allows scientists to change the DNA of many organisms, including plants, bacteria, and animals. Editing DNA can lead to changes in physical traits.	National Human Genome Research Institute[234]	9
Genetic engineering	A type of genetic modification that involves the intentional introduction of a targeted change in a plant, animal, or microbial gene sequence to achieve a specific result.	North Carolina State University[259]	24
Genetic modification	This includes the production of heritable improvements in plants or animals for specific uses, via either genetic engineering or other more traditional methods. It refers to a range of methods (such as selection, hybridisation and induced mutation) used to alter the genetic composition of domesticated plants and animals to achieve a desired result.	USDA,[241] North Carolina State University[242]	9
Greenhouse	A semi-controlled structure in which temperature and humidity can be managed for the cultivation and protection of plants. Greenhouses include a single layer of crops planted inside an enclosed space, and are constructed of glass or clear plastic to allow natural light in.	Agritecture[261]	38
Indoor / vertical farming	A form of controlled-environment agriculture (CEA) that consists of fully insulated indoor operations, producing crops on multiple levels solely using electrical lighting. Vertical farms, and CEA operations more broadly, are advertised as solutions to many environmental issues in food production in part because they are protected from the elements, and can be constructed in even the most extreme environments.	USDA[245]	10
Internet of Things (IoT)	A system of interrelated, internet-connected objects that are able to collect and transfer data over a wireless network without human intervention. IoT devices provide data and insights necessary to streamline workflows, automate processes, and compete more effectively in a changing business environment.	Aeris[235]	9
Machine learning	A branch of AI and computer science which focuses on the use of data and algorithms to imitate the way that humans learn, gradually improving its accuracy.	IBM[247]	10
Precision farming	Precision farming or precision agriculture is a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.	International Society of Precision Agriculture[246]	10

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Definitions of key terms, listed in alphabetical order:

Technology /Technique	Definition/Application	Source	Referred on page number
Plant-based alternatives	The "plant-based" alternatives sector refers to products made from plants that are alternatives to animal-based products. This includes plant-based meat, seafood, eggs, and dairy. Examples of alternatives include soy, wheat, potatoes, peas and pulses.	Good Food Institute[254]	16
Robotics	The engineering and operation of machines that can autonomously or semi-autonomously perform physical tasks on behalf of a human. Robots typically perform tasks that are either highly repetitive or too dangerous for a human to carry out safely.	Techopedia[249]	10
Satellite imagery	Photographs of Earth or other planets captured by satellites.	IGI Global[257]	18
Sensing	A technology that uses sensors to acquire information by detecting physical, chemical or biological property quantities and converting them into readable signals. Sensors offer real-time monitoring, including detection and reporting, as needed by a process.	Yokogawa[243]	10
Smart farming	The application of supplementary technologies to agricultural production techniques to help minimise waste and boost productivity.	National Center for Biotechnology Information[244]	10

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