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Innovation can accelerate the transition towards a sustainable food system.

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Supplementary information.

1. Assembling the inventories of technologies.

We collated a list of historical technologies from a synthesis of historical innovations in food systems that represent innovation in different periods of human history characterised by significant changes in sedentarism, mobility and invention (Table S1).

We collated an inventory of anticipated technologies that could accelerate progress towards achieving the food-systems sustainability. The inventory of possible technologies was assembled from literature searches, including the rapidly-expanding literature on transformation in food systems. The literature searches were complemented by researcher expert opinion (the authors). The inventory is shown in Table S2, with each technology classified based on a value-chain framework[1] into three categories: production; processing and distribution; and consumption. The technologies were further categorized into ten arbitrary "technology groups": cellular agriculture, digital agriculture, food processing and safety, gene technology, health, inputs, intensification, replacement food and feed, waste reduction, and "other" that contained disparate technologies not easily allocatable to the other groupings (such as battery technology and 3-D printing). The purpose of the groupings serves no purpose other than to facilitate presentation of the results.

The key criteria for inclusion in the inventory were (1) that technologies needed to have a direct impact on the key processes associated with the food system from production to consumption; and (2) that they represented "products" of some type (not necessarily physical products) that were applicable to the food system. The inventory in Table S3 contains some groupings of very similar technologies for which it would be difficult to separate the magnitudes and types of their impacts. To facilitate the scoring process for the evaluators, these were collapsed into the same "technology". For this reason, some of the entries in Table S2 are highly specific while others cover a group of different technologies. We acknowledge that there are many management and system-level interventions, as well as technologies from other sectors, that will undoubtedly also play critical roles in improving food systems (as well as raising the incomes of rural people), but these are not specifically covered here.

We classified each technology by its Technology Readiness Level[2,300-301].

1. The "Technology Readiness Level" is a systematic measurement system that supports assessments of the maturity of a particular technology[2]. It is made up of nine levels, as follows:

1: Basic principles observed and reported: Scientific, behavioural and market research paper studies; Lowest level of technology readiness.

2: Technology concept and/or application formulated: Practical, speculative applications invented. Potential user communities identified.

3: Analytical and experimental critical function and/or characteristic proof-of concept: Active Research and Development initiated. Critical elements identified and demonstrated with innovative users.

4: Component and/or validation in laboratory environment: Basic elements integrated to form a core practice-based technology. Initial design prototyped and tested.

5: Component and/or validation in relevant environment: Prototype 'implementation mechanisms' demonstrated along with core practice-based technology for users in a simulated environment (such as workshops).

6: System/subsystem model or prototype demonstration in a relevant environment: Implementation mechanisms refined and integrated with core practice-based technology and demonstrated in relevant environments.

7: System prototype demonstration in the environment: Implementation needs of mainstream users identified and integrated in prototype. Operational use by relevant users demonstrated across the community.

8: Actual system completed and "flight qualified" through test and demonstration: Technology adopted and distributed for widespread use across the community of practice.

9: Actual system "flight proven" through successful operations: Technology is used routinely within the community of practice. Best practices, quality assurance and body of knowledge in place.

2. List of historical innovations

Supplementary Table S1 summarizes a range of important innovations that have helped to transform and define the food system over time. This table should be treated as illustrative instead of exhaustive of the wide range of innovations across a broad range of disciplines that have shaped the food system and can be used to see a narrative evolution over time of the food system. Technologies are listed chronologically, although we should note that dating the moment an innovation comes into existence is challenging. This is true not only in deep prehistory, where innovations like the domestication of crops have been achieved at different moments in different unconnected geographies, but also in more modern times, where there is greater availability of documentation. The dates are provided with the goal of giving a wide narrative sweep of identified innovations and trying to tie them together with related technologies and innovations.

Supplementary Table S1. Summary of selected Historical Innovations. Categories: 1, Production; 2, Processing and Distribution; 3, Consumption; 4, Other.

Era	Category	Technology	Description	Year
Neolithic Revolution (Before 7,000 BCE)	2,3	Cooking[6]	While it is not possible to place the exact moment that cooking was invented, there is evidence of controlled fire use dating back to more than 1 million years ago	By 1 million BCE
	2	Grinding Stone[7]	Use of simple stone tools for preparation of foods and cereals is difficult to date, but certainly predates the invention of agriculture	By 30000 BCE
	2	Pottery[8]	One of the first and most important human innovations, the first examples of pottery were small fertility statues. Pottery and ceramics were critical for early storage of foodstuff	By 17000 BCE
	2,3	Drying/Curing[9]	Drying and curing are some of the oldest forms of food preservation, with examples of this behaviour dating well before the dawn of agriculture.	By 12000 BCE
	2,3	Fermentation[10,11]	Fermentation is an important food processing and preservation technique. Fermentation of meat products may date as far back to Neanderthal hunters. Examples of fermentation of plant products to	By 12000 BCE

Era	Category	Technology	Description	Year
			produce alcohol also dates far back in the Neolithic Era.	
	2,3	Bread[12]	The use of flour and yeast to make bread dates back deep into human history. This processing method allowed for increasing the nutrient availability of wheat grain.	By 12000 BCE
	1	Sickle[13]	First known tool dedicated to the harvesting of seeds from grasses	18000-8000 BCE
	1	Seed broadcasting[9]	First method used for planting seeds, and continued to be the primary method until the advent of the seed drill	By 13000 BCE
	1	Animal domestication[14]	First animals domesticated were dogs. Small ruminants were the first livestock animals to be domesticated	By 13000 BCE
	1	Deforestation[9,15,16]	Evidence of deforestation in the form of different agricultural practices like slash a burn date to early agriculture	By 12500 BCE
	1	Hoe-farming[9]	One of the most important agricultural tools, developed to help with preparing the soil (tilling) and weeding	By 12500 BCE
	4	First permanent settlements[17]	Catalhöyük is one of the earliest examples of what we would now recognize as a city and is dated to 7400-6000 BCE. Earlier settlements were likely formed even around or before the domestication of plants	13000-11000 BCE
	1	Plant Domestication[18]	Plant domestication began in different parts of the world at slightly different times, but in general focused on the domestication of a selection of key grasses and roots	By 12500 BCE
	2	Granary[19]	Examples of granaries to store surplus grains have a long history dating all the way back to the beginning of agriculture, and may in fact predate agriculture	By 11000 BCE
	2	Oven[20]	Ovens are among the first examples of sedentary societies as they demonstrated construction of reusable cooking apparatus as opposed to the open pit cooking more common among nomadic groups	By 10000 BCE
	1	Terraced Farming[21,22]	One of the first practices of controlling the environment to increase agricultural yields. Terrace farming allowed cultivation along steeper topologies and allowed control of contours and even microclimates. Improved water drainage and soil fertility	By 6000 BC
	1	Eel Farming[23]	First example of aquaculture, with the domestication of eels in Australia	By 6000 BCE
	1	Crop Rotation[24,25]	Early in the development of agriculture Neolithic farmers started to practice rotating crops, to improve crop yields, and improve pest management	By 6000 BCE
	1	Manure/Compost Use[26]	The domestication of livestock not only served to provide a source of food and draft power, but also provided key soil inputs	By 6000 BCE
	2,3	Wine[27]	The invention of alcoholic beverages like wine date back to near the beginning of civilization	By 6000 BCE
	2	Jugs[27]	An important innovation. Ceramic jugs permitted the storage and movement of liquids	By 6000 BCE

Era	Category	Technology	Description	Year
Ancient History (7,000 - 800 BCE)	2,3	Evidence of Cheesemaking[28]	Cheese making was an important step forward in food preservation, allowing milk to be stored in a solid state that was easier to move	By 5000 BCE
	4	Writing[29]	The invention of writing by the Sumerian and Egyptian civilizations marked a key step forward in increasing the complexity of societies	3000 BCE
	1	Irrigation[30]	First major irrigation works were established in the Indus and Nile River Valleys. They allowed for better management of weather variability by being able to use surface water for agriculture	3000 BCE
	1	Animal drawn ard[31]	The first animal drawn plough. The ard greatly increased the ability to open areas to agriculture that previously would have been too difficult	3000 BCE
	2,4	Galleys[32]	Critical advances in navigation and shipping opened trade networks across the Mediterranean, allowing for the flow of goods, and ideas	3000 BCE
	2,4	Wheeled Transport[33]	The invention of the wheel was a major advance that greatly increased the efficiency of transportation on land	By 2000 BCE
	1	Shalihotra Samhita (veterinary)[34,35]	The Shalihotra Samhita is an early Indian treatise on veterinary medicine (hippiatrics), likely composed in the 3rd century BCE.	2350 BCE
	1	Sulphur used as pesticide[36]	The application of chemicals to attempt to control pests dates far back into antiquity. There is evidence in Homer's Odyssey of the use of sulphur as an insecticide. There is also documentation on the use of arsenic as a pesticide in the last several centuries BCE	By 1500 BCE
	1	Grafting[37]	Grafting is an important tool in the horticulturalist's toolbox, allowing for the controlled transfer of genetic traits across different plants	2000-600 BCE
	1,4	Aqueducts[38]	The first aqueducts date back to the Indus Valley Civilizations, and were the first construction to transport surface water across distance	By 1000 BCE
	1	Fish farming[39]	The domestication of fish came much later than terrestrial animals, with Chinese farmers domesticating the common carp around 500 BCE	By 500 BCE
	1	Scythe[40]	An improvement in agricultural tools. The scythe was designed for harvesting cereals	By 500 BCE
	4	Coinage[41]	The invention of money predates coinage. Nevertheless, coinage was an important step towards improved commerce	By 500 BCE
	2	Horse driven mill[42]	Carthaginians invented one of the first animal powered mills, which would be the forbearer of a great many different types of mills, that would increase the speed and efficiency of milling cereal seeds into flour	500 BCE
	1	Incubator[43]	Artificial incubators applied heat to special rooms to help keep eggs warm	400 BCE
	2	Tilt-hammer[42]	The tilt-hammer was an improvement on the mortar and pestle and allowed the application of force more effectively in the grinding of seeds and other materials	By 100 BCE

Era	Category	Technology	Description	Year
Classical Antiquity (1,000 BCE - 600 CE)	2	Water Mill[44]	A watermill is a mill that uses hydropower. The water wheel may have originated in the ancient Near East in the 3rd century BC for use in moving millstones and small-scale grain grinding	200-300 BCE
	2,4	Geographic Coordinate System[45]	A geographic coordinate system is a coordinate system that enables every location on Earth to be specified by a set of numbers, letters or symbols. The invention of a geographic coordinate system is generally credited to Eratosthenes of Cyrene, who composed his now-lost Geography at the Library of Alexandria in the 3rd century BCE.	300 BCE
	2,4	Compass[46]	A compass is an instrument used for navigation and orientation that shows direction relative to the geographic cardinal directions (or points). The compass was an important innovation that facilitated travel and exploration.	300-200 BCE
	4	Limited Desalination[47]	Desalination is a process that takes away mineral components from saline water. Desalination has a long history, with references to desalination found in the Bible, as well as in the writings of Aristotle who recognized the distillation could turn salt-water sweet.	500-100 BCE
	4	Astrolab[48]	An astrolabe is an inclinometer, historically used by astronomers and navigators to identify astronomical objects, to estimate latitude, to triangulate, and to survey. An early astrolabe was invented in the Hellenistic civilization 220 and 150 BCE.	220-150 BCE
	1	Multi-tube seed drill[49]	A seed drill is a device that sows seeds, systematically placing individual seeds in the soil and covering them. The seed drill increased the efficiency and regularity of planting, improving crop distribution and yields. Multi-tube iron seed drills were invented by the Chinese in the 2nd century BCE.	200 BCE
	1	Gaelic Reaper[40,50]	The reaper was an improvement on the scythe and was developed by Roman farmers.	50 CE
	2,4	Roman Roads[51]	Roman roads were physical infrastructure vital to the maintenance and development of the Roman state and were built through the expansion and consolidation of the Roman Republic and the Roman Empire. The roads served as critical transportation and communications infrastructure, which helped to unified much of the Mediterranean in one large socioeconomic block.	100BCE-500 CE
	1	Biological pest control[52,53]	Biological control or biocontrol is a method of controlling pests such as insects, mites, weeds and plant diseases using other organisms. First early efforts of using biological controls may have been implemented as early as 300 CE by botanists in the Jin Dynasty who used ants to help control insect damage to citrus crops.	300 CE
	2	Wind grain mill[54]	A windmill is a mill that converts the energy of wind into rotational energy by means of vanes called sails or blades. The first windmills were developed to	500-900 CE

Era	Category	Technology	Description	Year
			automate the tasks of grain-grinding and water-pumping and the earliest-known design is the vertical axis system developed in Persia about 500-900 A.D.	
	4	Decimal Numeral System[55]	The decimal numeral system was developed by Indian mathematicians, and it is a place-value notation for the representation of numbers using the powers of 10. Its use was spread to Europe by Muslim traders, and has over time become the dominant numeral system	700 CE
Post Classical (700 - 1300 CE)	4	Inoculation[56]	The terms inoculation, vaccination, and immunization are often used synonymously to refer to artificial induction of immunity against various infectious diseases. Inoculation originated as a method for the prevention of smallpox by deliberate introduction of material from smallpox pustules into the skin. Inoculation has ancient origins and the technique was known in India and China. The earliest hints of the practice of inoculation for smallpox in China come during the 10th century.	900-1000 CE
	1	Terra preta[57,58]	In the Amazonia, indigenous populations applied slash and burn techniques to insert charcoal (biochar) into soils to produce enriched soils that could support more intensive agriculture.	By 1000 CE
	1	Companion cropping in rice[59]	Companion planting in gardening and agriculture is the planting of different crops in proximity for several reasons including pest control, pollination, providing habitat for beneficial creatures, maximizing use of space, and to otherwise increase crop productivity. In China, mosquito ferns (Azolla spp.) have been used for at least a thousand years as companion plants for rice crops. They host a cyanobacterium that fixes nitrogen from the atmosphere, and they block light from plants that would compete with the rice.	1000 CE
	1,2	Roller Gins[60]	The roller gin provided the first mechanical process for separating cotton lint from the seed, a critical innovation that would contribute to cotton becoming the dominant fibre crop a few centuries later	1100-1300 CE
	2,4	Caravel[61]	The caravel was a highly manoeuvrable sailing ship. The caravel was an improvement on Islamic ships, and facilitated European exploration in the “Age of Discovery”	1200 CE
	2,4	Portolan charts[62]	Portolan or portulan charts are ancient nautical charts, first made in the 13th century in the Mediterranean basin and later expanded to include other regions. They were useful navigational tools that helped facilitate trade and exploration	1200 CE
Early Modern Period (1300 -	1	Heated greenhouse[63]	The first description of a heated greenhouse is recorded in a Korean cookbook titled Sanga Yorok written in 1459. As described, it used underfloor heating system (“ondol”), cob walls for insulation, and semi-transparent windows for light control.	1400s CE
	4	Rain Gauge[64]	The first known rain gauge was invented in Korea in 1441. Improved observation of weather phenomenon	1441 CE

Era	Category	Technology	Description	Year
			has been an important ongoing development for farming	
	1	Enclosure[65]	Enclosure was the century long process of enclosing of communal lands into single farmer plots. The enclosure is one of several advances credited with the increased productivity of agriculture in Britain, during the British Revolution	1400-1800 CE
	1	First hydroculture text[66]	The first written example of hydroculture was written by Francis Bacon, and describe ways of growing plants in water solutions	1627 CE
	1	Norfolk Crop Rotation[67]	The Norfolk crop rotation expanded the number of crops rotated from 3 to 4, by adding turnips to the rotation. This rotation helped to increase agricultural productivity	1600-1700 CE
	1	Convertible Husbandry[68]	Also known as alternative husbandry, this process increased the amount of time land was kept as pasture or fodder in crop rotations, increasing the number of animals that could be supported by the land	1500-1800 CE
Industrial Revolution (1700 – 1850 CE)	1	Tull's Horse-Drawn Hoe[69]	Jethro Tull developed the horse-drawn hoe which allowed efficient soil shaping and weeding, reducing the amount of human labour required for the task.	1701 CE
	1	Tull's Seed Drill[70]	Around the same time Tull developed the horse-drawn seed drill, which allowed efficient planting of seeds in neat rows, reducing the amount of human labour required for the task.	1701 CE
	4	Mercury Thermometer[71]	The mercury thermometer was developed by physicist Daniel Gabriel Fahrenheit in the Netherlands in 1714. It is used to measure temperature of various mediums including air, water and soil with many applications across medicine, agriculture and meteorology among other disciplines. The mercury thermometer is still widely in use today.	1714 CE
	2,4	Sextant[72]	The sextant is an instrument primarily used for navigation. It can be used to measure the angular distance between an astronomical object and the horizon. It is said to have been first implemented by John Hadley and Thomas Godfrey in 1731.	1731 CE
	1	Mouldboard plough[73]	The plough is used to turn over the top layer of soil to bring nutrients to the surface. The mouldboard addition to the plough reduced the time taken to plough a field, greatly improving labour efficiency.	1700s CE
	1	Mass production of the plough[73]	Improvements to the plough applying mathematical modelling allowed for its increased standardization. Standard designs would allow for its mass production, helping to reduce prices and encourage its wide adoption	1700s CE
	1	Leicester sheep bred[74]	This breed of sheep was developed by Robert Blakewell who was the first to use modern breeding techniques in livestock selection. This breed was known to gain weight rapidly and produce less waste when slaughtered. It played a key role in the colonisation of Australia and New Zealand by the British.	1755 CE

Era	Category	Technology	Description	Year
	2	Ribbing machine[75]	The Derby Rib machine was invented by Jedediah Strutt in 1758. The derby rib attached to a stocking frame and allowed for the knitting of ribbed cotton stockings, which became very popular. This improvement in clothing manufacturing allowed for much cheaper and faster production of stockings to satisfy growing demand for cotton clothes.	1758 CE
	1	1st Veterinary School[76]	The first veterinary school was established in Lyon in 1762 in response to a cattle plague among French cattle.	1762 CE
	1	Longhorn cattle bred[74]	Robert Blakewell further contributed to livestock breeding through the development of the English Longhorn cattle breed, one of the first breeds bred primarily for meat production	1769 CE
	2	Water frame[77]	The water frame is a water powered spinning frame developed by Richard Arkwright that enabled spinning of 128 cotton threads at a time.	1769 CE
	1	Artificial insemination[78]	The first successful artificial insemination of an animal was in a dog, recorded by Spallanzani in Italy, though it was not until 100 years later when others reported that the technique had been used in other animals.	1780 CE
	2,4	Watt Engine[79]	Thomas Watt developed the first practical steam engine. It is known for its use in the Whitbread London brewery for grinding and lifting malt and other processes.	1781 CE
	2,4	1st steamboat[80]	John Fitch was an American who adopted the Watt steam engine for use in boats. Steamboats would revolutionize sea travel through the 19th century, supplanting sailboats first in reliability and later in speed.	1783 CE
	1,2	Thresher[81]	The first threshing machine was invented by Andrew Meikle and is used to remove the stalk and husk from grain. Threshing machines would reduce the amount of labour needed for harvesting of cereals.	1786 CE
	1,2	Cotton Gin[82]	The cotton gin is a machine that separates cotton fibres from their seeds. Whilst handheld machines were in use from as early as 500 CE, the first mechanised cotton gin was invented in 1793, greatly improving efficiency.	1793 CE
	4	Vaccines[83]	The first vaccines were developed against the smallpox virus. These vaccines were developed by isolating a related virus (cowpox) from cow lymph nodes.	1797 CE
	2	Powdered Milk[84]	The first production process was invented in 1802, followed by commercial production in 1832. This process gave the duel benefit of greatly increasing shelf life of milk and reducing its bulk allowing for mass transportation.	1802 CE
	2	Cotton velvet[85]	Velvet has traditionally been made from silk, but during the industrial revolution methods to produce velveteen and other velvet-like materials out of cotton were developed. These techniques further	By 1803 CE

Era	Category	Technology	Description	Year
			solidified the prominence of cotton as the premier fibre.	
	2,4	Steam Locomotive[79]	The first steam engine powered locomotive was invented by Richard Trevithick in Britain and was first operated in 1804. Steam locomotives were used widely for transport for at least the next 100 years, and were essential in connecting the interior of North America with the coastal urban areas, allowing agricultural areas to access national and international markets.	1804 CE
	2	Canning[86]	Nicolas Appert developed a method of selling food in glass jars in response to incentives from the French government to develop a cheap and effective method of preserving food during the Napoleonic Wars. This was further adapted and improved with the use of steel and tin cans to supply the British royal navy by 1820	1806 CE
	2	Public Slaughterhouses[87]	The first public slaughterhouse or abattoir emerged in France in 1810 in response to concerns of public hygiene and as part of the broader transition from an agrarian to industrialised food system.	1810 CE
	4	Luddite Riots[88]	The Luddite Riots was a social movement against the changes broadly brought by the industrial revolution, and specifically against the wide-framed automated looms which could be operated by relatively unskilled labour, thereby threatening the jobs of high skilled weavers.	1811 CE
	4	UK Corn Laws[89]	The corn laws were a series of tariffs and trade restrictions imposed on imported grains in favour of domestic production. Landowners largely benefited at the expense of higher food prices for the public which subsequently hampered economic growth of other sectors. The laws were repealed after the onset of the Irish famine.	1815 CE
	2,4	Chronometers[90]	The chronometer is a time piece that allows the accurate measurement of longitude at sea. Its invention enabled the British to dominate both naval and mercantile navigation of the oceans.	1800-1850 CE
	1	Hussey Reaper[91]	A reaper is a farm tool that can be used to harvest crops (mainly cereal grasses). Variations of reapers were in use since the Roman era. Mechanised versions were the subject of several inventors in the 19th century. Obed Hussey successfully patented the Hussey Reaper in 1833.	1833 CE
	4	Electric Telegraph[92]	The electrical telegraph uses electrical signals to convey a coded message via a radio circuit and was the first form of electrical telecommunications. This invention increased the speed of communication and combined with the expanding rail system improved transportation logistics. The telegraph was essential not only for improved communication, but better time keeping, and weather observation.	1835 CE
	2	Grain Elevator[93]	The grain elevator was used to stockpile large quantities of grains, scooping large quantities into	1842 CE

Era	Category	Technology	Description	Year
			silos or equivalent storage facilities. Prior to the invention of the grain elevator, grain was handled in bags rather than in bulk.	
	4	Water Turbine[94]	James Francis developed the first modern water turbine. It greatly improved efficiency of water wheel power generation and was critical for industrial power before the widespread adoption of electricity, and were then important in the production of hydroelectricity.	1849 CE
	4	Machine Tools[95]	Machine tools were tools designed specifically to produce metal parts. They were critical in the standardization of tools, which allowed for increased mechanisation and the rapid production at scale of new tools and machines.	1800s CE
Machine Age (1850 - 1930 CE)	2	1st practical refrigerator[96]	Artificial refrigeration is a key modern food preservation technology. The use of ice boxes and ice cellars have been used since pre-history for the preservation of food. Initial attempts at artificial refrigeration date to the mid-1700s, with the first practical refrigeration machine developed by Jacob Perkins	1834 CE
	4	Met Office Established[97]	Improved prediction of weather has been a key technological improvement that has permitted better planning of agricultural production amongst many other things. Attempts at weather forecasting can be seen throughout history. Modern scientific forecasting started to evolve in the second half of the 19^{th} century[98]. The Met Office was the first agency dedicated to weather forecasting.	1854 CE
	2	Milking Machine[99]	The development of vacuum technology that is used in milking machine started in 1800s. But the first successful commercial milk machine was released in England in 1889.	1860 CE
	4	First Internal Combustion Engines[100,101]	The first internal combustion engine, a coal gas-fired engine, was developed by Jean Joseph Etienne Lenoir and patented in 1860. Nikolaus Otto, would develop the first commercial 4-stroke engine a few years later patenting the design in 1867.	1860s CE
	2	Pasteurization[102]	Pasteurisation is a food preservation method that can preserve food without the need for complete sterilisation. The name honours Louis Pasteur, whose discoveries in the 1860s improved food storage techniques, better preserving food quality over time.	1862 CE
	1	Mendel's Law of Inheritance[103]	The application of Mendel's three laws made it possible to predict the characteristics of offspring produced by parents of known genetic composition. This helped to shape the advances in genetic technologies to selectively breed plants and animals to produce more useful hybrids.	1865 CE
	1	Barbed Wire[104]	Adoption of barbed wire greatly reduced the cost of fences, and increased farmers' ability to protect their land from encroachment and hence improved property rights and agricultural development.	1867 CE

Era	Category	Technology	Description	Year
	1	DDT Synthesized[105]	The burgeoning clothing industry faced the bane of insects. Advances in synthesizing new dyes did not just focus on colour characteristics but also explored compounds that would help fabrics resist insects. These advances accelerated in the second half of the 19th century. DDT was discovered during this time (1873), although its use as a synthetic pesticide wasn't appreciated until much later when it was patented in 1940	1873 CE
	4	First synthetic Antibiotics[106,107]	While natural antibiotics have been used for a long time, the first attempts to develop synthetic antibiotics started in the late 1800s. Pyocyanase, the first modern antibiotic, was developed by Rudolf Emmerich and Oscar Löw. By the 1890s, the antibiotic properties of penicillin were beginning to be understood, although, the synthesis of significant quantities of antibiotics like prontosil (1930s) and penicillin (1940s) wouldn't occur for several more decades.	1890s CE
	1	Petrol Tractor[108]	John Fowler, an English engineer, pioneered the use of steam engines ploughs in the 19th century. Building on these designs and advances in internal combustion engines, field tractors started to come to market. The tractor would displace animal power on the farm, freeing up farm production to feed draft animals.	1892 CE
	1	Commercial Hybrids Crops[109,110]	Improved understanding of the genetics of maize (and other crops) at the end of 19th century laid the foundation of scientific knowledge that would allow for the development of the first commercial maize hybrids in the 1920s and 1930s	1890-1930 CE
	2,4	First Commercial Auto Truck[111]	Gottlieb Daimler, German automotive pioneer built the first auto truck, with the first commercial truck hitting the market in 1908.	1896 CE
	2	Use of Artificial Preservatives[112]	US approves the use of sodium benzoate as an additive to certain foods. Food preservatives would be another new technology that helped to extend the shelf life of foods.	1908 CE
	1	Industrial Nitrogen Fixation[113]	The element nitrogen was discovered in 1772 by Daniel Rutherford, with many nitrogen compounds like nitrous oxide and ammonia identified shortly after. The importance of nitrogen in crop growth became understood in the 19th century. Fritz Haber would first synthesize ammonia in 1909 with Carl Bosh industrializing the process in 1913.	1910s CE
	1	Industrial Animal Feed Concentrates[114]	Scientific animal feed standards began to be developed in the 19th century. These standards initially were crude, but over the course of the century became increasingly refined with more nutrient specific targets. By the end of the 19th century industrial processing of formulated feeds was taking place. In the early 20th century, these processes continued to improve with the development of feed	1900-1920 CE

Era	Category	Technology	Description	Year
			concentrates (feed pellets) greatly increasing feed efficiency in the USA and Europe	
	3	Mandated Food Fortification[115,116]	The first modern example of nutrient supplements is probably in the form of adding iodine to salt, suggested by Boussingault in the 1830s. However, major efforts at food fortification to correct for nutritional deficiencies wouldn't happen until the interwar period in the 20th century	1920s CE
	1,4	Numerical Weather Prediction[98,117]	First attempts at statistical estimation and prediction of weather patterns. Initial attempts were not particularly accurate until the 1950s with the availability of more powerful computers	1920 CE
	4	Synthetic Rubber[118]	Pneumatic tires were invented in the mid-1800s, and were essential for the burgeoning bicycle, automobile, truck, and tractor industries. Dramatic growth in demand for these products led to a boom in the demand for natural rubber, which could not always be met. This led to rising prices of natural rubber and pushed the development of synthetic alternatives. In the 1920s, scientists in Germany and the USSR developed the first commercial processes to synthesize rubber.	1920s CE
	1	Crop Dusting[119]	Using aerial technology to spray crops started in 1920s and 1930s. It was adopted mainly in the USA and to a lesser extent in other nations. This practice facilitated the application of pesticides on broad acre crops while reducing labour requirements.	1920s CE
	2,3	Modern Fast Food[120]	The first fast food restaurant chain (White Castle) was established in the 1920s in the US. In the 1940s and 1950s fast food chains developed further and new chains such as MacDonald and KFC were opened. These chains would revolutionize food service, by standardizing food processing and preparation techniques. Many of these firms would also be important in revolutionizing the food advertising sector.	1920s CE
	1	Backcrossing[121]	Backcrossing, or the plant breeding practice of crossing a hybrid with one of its parents, was an important practice used to control desirable genetic characteristics and was one of many breeding improvements that contributed to the 'green revolution' in the 1950s and 1960s.	1920s CE
	2	Flash Freezing[122]	Flash freezing was a new preservation technique, that helped to prevent the formation of ice crystals, and thereby improved the quality and durability of frozen foods	1929 CE
	1	Hydroponics Coined[123]	Hydroponics is the agricultural practice of growing crops in water solutions. Research into the necessities of plant growth allowed for the soilless cultivation of plants, with W.F. Gericke coining the term "hydroponics" in the 1930s.	1930 CE
Gree n	4	Large scale desalination of salt water[47]	Desalinisation has been practiced since ancient times. However, it wasn't until the 1930s that the industrial	1930s CE

Era	Category	Technology	Description	Year
			process of producing fresh water from seawater was achieved.	
	1	Battery Cage[124,125]	Housing system primarily used for poultry and egg production, where the arrangement of cages in rows and columns is like an artillery battery. The development of battery brooding greatly reduced the amount of space needed for poultry production. The practice would however come with controversy as the increasing crowding of animals in poultry production has raised significant concerns with respect to animal welfare.	1930s CE
	2	Mobile refrigeration[126–128]	Refrigerated transport relying on ice has a long history. Through the 19th century the use of ice-box transport was important in maintaining cold chains in the USA. The first refrigerated trucks were developed in the 1920s for ice cream vendors, with the first modern refrigerated trucks developed in the 1930s and 1940s. These advances allowed for the expansion of cold chains, and improved food preservation and distribution significantly.	1940 CE
	1	1st modern herbicide[129]	The first modern herbicide, 2,4-D was developed during World War 2 in the UK and USA. It was commercially released by 1946 and helped to increase crop yields by better controlling weeds.	1940 CE
	4	Bretton Woods Agreement[130]	The Bretton Woods Agreement created a system of international institutions that have underpinned the liberal world order since WWII. They created rule-based international systems that have helped to formalized and regulate international affairs and commerce.	1944 CE
	1	No-Till Agriculture[131]	Historically tilling has been an important tool for weed control. With the introduction of herbicides in the 1940s, the opportunity of implementing high yielding no-till agriculture became possible. The implementation of no-till agriculture has had many benefits including reduced soil erosion, and better soil water retention	1940s CE
	1	Shuttle breeding[132]	Improvements in plant breeding stared to take momentum in the 1940s and continued to progress ever since. Shuttle breeding (simultaneous breeding across multiple agroecologies) permitted for more rapid development of hybrid crops, which contributed to the Green Revolution in the 1950s and 1960s.	1945 CE
	2,3	Commercial microwave[133]	Microwave heating technology was invented after WW II, although microwave ovens wouldn't become commercially available until the late 1960s.	1947 CE
	1	Growth Supplements[134]	The first demonstration of growth stimulation in cattle with hormone supplementation took place in 1947 by investigators at Purdue University using diethylstilbestrol (DES) in heifers.	1947 CE
	1	Armenian Hydroponicum Tower[135]	The first example of vertical farming of vegetables was implemented in the USSR in support of efforts to explore space.	1951 CE

Era	Category	Technology	Description	Year
	2,4	Polyethylene[136]	The development of polyethylene began in the 1930s and has been a revolutionary material in the field of plastics.	1953 CE
	2,3	TV dinner[137]	The creation of the premade TV dinner which included a main course and several side dishes that just needed to be reheated was an important innovation in the food system, emphasizing the importance of comfort and speed in food preparation.	1953 CE
	1	Using semi-dwarf varieties[132,138]	The first semi-dwarf hybrids of wheat were developed in Japan in the 1930s. They would be crossed with Mexican varieties by Norman Borlaug in the 1950s helping to launch the Green Revolution	1950-1960 CE
	4	1st Desalination Membranes[47]	Membrane technologies were developed in the late 1950s, with the first practical applications of the technology implemented in the 1960s by General Atomics and DuPont. Membrane technologies were important at reducing the energy requirement for water desalination.	1960s CE
	1	Hoop Houses[139]	Producing vegetables in glasshouses dates to Roman times. However, its large-scale adoption began in the 1950s and 1960s.	1960s CE
	4	ARPANET[140]	ARPANET was a precursor to the World Wide Web. It was a computer network that pioneered the TCP/IP communication protocol	1960-1970s CE
	2,3	HF Corn Syrup[141]	High fructose corn syrup was discovered by Japanese scientists in the 1960s. High fructose corn syrup has become an important alternative to sugar in the USA, with it first being marketed by the Clinton Corn Processing Company in the 1970s.	1965-1970 CE
	2,4	GPS[142]	The Global Positioning System was launched by the United States in 1973 and connected a system of satellites to allow for detailed spatial coordination. Originally created for military use, it would later be opened to peaceful uses and has become an essential tool in transportation logistics.	1973 CE
	4	1st Mobile Phone[143]	Cordless phones that worked based on radio signals. Initial cordless phones were expensive and not particularly mobile, but within a few decades increasingly advanced and cheap mobile phones would radically disrupt the telecommunications industry.	1973 CE
	4	First Personal Micro-Computer[144]	The personal computer put significant computation power at the hands of an increasing market of users. The advances in productivity of this advance would take some time to be realized, however.	1975 CE
Information Age (1980 - Present)	1	Chicken Harvester[145]	A machine that automates the gathering of chickens for slaughter. This innovation greatly increased the efficiency of poultry production, while reducing the labour required for chicken slaughter	1980s CE
	1	Marker-assisted Selection[146,147]	An advance in breeding, where a trait is selected based on it being linked to a marker of another train, which has increased the efficiency of breeding significantly	1986 CE

Era	Category	Technology	Description	Year
	1	CRISPR[148]	Advance in genetics, which allows for the targeted insertion or removal of pieces of DNA.	1987 CE
	1	Bt Tobacco[149,150]	First example of genetically modified crops. Tobacco was genetically modified to introduce BT genes to help increase plant resistance to the tobacco hornworm. This technique would be applied to several Bt crops including tomatoes, and potatoes.	1987 CE
	4	World Wide Web[151]	The World Wide Web, which underpins the internet, is a massive international computer network. This ICT infrastructure would be critical for the digital revolution	1989 CE
	4	1st Smartphone[152]	Advance in mobile phone technologies. It greatly increased the computational power available at hand.	1995 CE
	1,2,4	Precision Technologies[153]	A combination of technologies that have allowed for the better collection of data, to more precisely tailor agricultural management (irrigation, pesticides, fertilizer, planting, etc.)	1990s CE
	1	Roundup Ready Soybean[154]	First genetically modified crop designed to be resistant to chemical herbicides (glyphosate), allowing weeds to be targeted without harming the crop	1996 CE
	1	Biofortification of Crops[155,156]	A process of breeding or modifying crops such that their nutrient composition is changed.	1990s CE
	1	Dolly the Sheep[157]	The first example of a clone of livestock	1997 CE
	1	Agricultural Drones[158]	Unmanned aerial vehicle applied for the first time for agricultural purposes	2000 CE-Present
	4	First Blockchain[159]	An open, distributed (not centralized) ledger that can record transactions between two parties in a verifiable and permanent way. Has the potential to underpin a range of new technologies including cryptocurrencies, new contract software, amongst many more	2008 CE
	1	Cultured Meat[160]	The process of producing meat using in vitro cultivation of animal proteins in a laboratory environment	2000 CE-Present

3. Future technologies

Supplementary Table S2. Summary of Anticipated Technologies. Categories: 1, Production; 2, Processing and Distribution; 3, Consumption; 4, Other.

Category	Technology group	Technology	Description and examples	Company
1,3	Cellular agriculture	Artificial meat/fish[161,162]	Artificial or cultured meat, also called clean meat, synthetic meat or in vitro meat, is meat produced by in vitro cultivation of animal cells, instead of from slaughtered animals. Cellular agriculture allows engineers to grow skeletal muscle tissue outside of an organism.	https://www.justforall.com/en-us/stories/clean-meat https://www.mosameat.com/ https://finlessfoods.com/
1,3	Cellular agriculture	Artificial products[162,163]	Products (milk, coffee, fragrances, silk, leather) produced by in vitro cultivation.	http://www.jcpuleather.com/
1,2,3	Digital agriculture	Robotics[164–167]	The use of robotics in agriculture and farm management. This includes autonomous cropping implements (planting, surveying, nursing and harvesting robots) and “Soft grasp” technology for harvesting, handling, and other complex dextrous operations.	http://mirobot.co.il/
1	Digital agriculture	On-field robots[168,169]	On-field robots to monitor crops and animals. This includes continuous data capture for health, automating welfare inspections) and Digital agriculture (weeding, drilling).	
1,2	Digital agriculture	Pest control robotics[170,171]	Robotics for pest control or automatic pest surveillance. This includes weed controller, weed mapper, robotic gantry for macro pesticide spraying and fertiliser spraying, micro sprayer systems and continuous monitoring insect detection tech.	http://rapidaim.io/
1	Digital agriculture	Sensors for soil[164,172]	Use of sensors to measure key biological function of the soil e.g. soil moisture, N, P, K, micronutrients. Data from the sensors can be sent to the cloud where it can be accessed from any mobile or fixed device.	https://www.cropx.com/
2,3	Digital agriculture	Nanotechnology[173,174]	The use of nanotechnology in the food system. The usage of nanoscale materials in sensing and detection applications (e.g. screen food for food pathogens) and original product packaging with antimicrobial nanoparticles, and agrochemicals and nutrients that have been nano-encapsulated.	
1,2,3	Digital agriculture	Internet of Things[175,176]	The “Internet of Things” can provide a technological universe, in which many physical objects or “Things”, such as sensors, everyday tools and equipment enhanced by computing power and networking capabilities will be able to play a role, either as single	

			units or as a distributed collaborating swarm of heterogeneous devices. The management and analysis of Internet of things data ("Big Data") can be used to automate processes, predict situations and improve many activities including information storage and transactions (e.g. blockchain), even in real-time.	
1	Digital agriculture	Disease/pests early warning[177,178]	Early warning systems for plant disease and pests - A collaborative effort to utilize advancements in data collection and analysis to identify and communicate real-time information on plant disease and pest outbreaks that might affect post-harvest supply chains in emerging markets. EWS could be championed by governments, academic or research institutions, or through a public-private-partnership model in conjunction with industry.	
2,3	Digital agriculture	Traceability technologies [177,179]	Improved traceability technologies in the food system. A combination of tracking technologies and an easy-to-use online or mobile interface that can be used to trace product movement across the supply chain. These include latest technological advancements such as innovative implementations of Radio frequency identification (RFID) that can make to increase the sales of wheat flour, or allowing the consumer to know the full record of the IV range products through the smartphone; knowing the food authenticity with an isotope analysis or by analysing the DNA sequences.	
2,3	Digital agriculture	Farm-to-fork virtual marketplace[177,180]	The Farm-to-fork virtual marketplace is an online or mobile phone-based platform that connects farmers to food purchasers, including end-consumers but also restaurants and hotels. This farmer to-market connection allows for more efficient and timely supply chains.	
1,2,3	Digital agriculture	Big data[181,182]	The use of inputs and outputs information from big data analyses and climate services in the agricultural sector. Big data are being used to provide predictive insights in farming operations, improve decision making and farm extension services, drive real-time operational decisions, and redesign business processes for game-changing business models as well as using big data to find building blocks for food in so far not or little used plant species.	
3	Digital agriculture	Smartphone food diagnostics[183,184]	Smartphone-based food diagnostic technologies for many applications including food safety analysis and environmental monitoring.	

1,2,3	Digital agricultur e	Drones[185,186]	Use of drones in the food system. This includes sensing, monitoring, and Digital agriculture in agricultural systems and direct delivery to of food via drones.	
1,2,3	Digital agricultur e	Nano-drones[187,188]	The use if nano-drones in the food system. This includes their use in value chains, breeding, research, crop identification.	
1,2,3	Digital agricultur e	Artificial intelligence[181,189]	Use of Artificial Intelligence in agriculture. This includes the use of artificial intelligence advisors and managers.	
1	Digital agricultur e	Assistive exoskeletons [190,191]	Development of assistive exoskeletons such as the Wearable Agri-Robot, whichare designed as an exoskeletal mechanism to assist in the wearer's work.	
2	Digital agricultur e	Intelligent food packaging[192,193]	Intelligent food packaging technology (e.g. micro-chips) that contains sourcing, safety and traceability information regarding the production, processing and environmental footprint of food.	
2	Digital agricultur e	Advanced sensors[194,195]	Sensors such as near-infrared spectrometers and hyperspectral imaging, combined with computer vision/smart phones, provides data on food quality, safety, provenance/authenticity, with benefits for reduced waste and health benefits.	
2	Digital agricultur e	SERS sensors[196,197]	Surface-enhanced Raman spectroscopy or surface-enhanced Raman scattering (SERS) is a surface-sensitive technique which is able to detect single molecules, as a promising chemical analysis of agricultural products and foods.	
1	Digital agricultur e	Improved climate forecasts[198,199]	Use of improved seasonal forecasts in agriculture. This includes decision-support systems using seasonal climate forecasts to manage risk such as under- or over application of fertiliser.	https://www.yieldprophet.com.au/yp/Home.aspx
1	Digital agricultur e	Omic data use[200,201]	Use of artificial intelligence and machine learning tools to identify better genomic and/or phenomic predictors of breeding targets from big data.	
1	Digital agricultur e	Data integration[202,203]	Integration of genetic, phenomic and environmental/climatic data to optimise production.	
1,2	Other	Battery technologies [177,204]	Improvements to battery technologies to enable them to hold a large charge, for long periods of time, and at low cost.	
1	Inputs	Soil additives[205,206]	Soil additives that optimise water use or increase soil fertility. Can be used to assist plant growth in infertile (e.g. desert) environments. Examples include BountiGel®, Liquid NanoClay, biochar, and compost.	http://moasisgel.com https://www.desertcontrol.com/liquidnanoclay/
1	Inputs	Micro-irrigation/	The use of micro irrigation, fertiliser, fertigation systems in farming systems to optimise water and nutrient use, increase	

		fertigation[207,208]	productivity and minimise environmental losses of nutrients.	
1	Inputs	Nanofertilisers[209,210]	Use of nanofertilisers in the agricultural system. Nanoparticles have high surface area, sorption capacity, and controlled-release kinetics to targeted sites making them "smart delivery system." Nanostructured fertilizers can increase the nutrient use efficiency through mechanisms such as targeted delivery, slow or controlled release.	
1	Inputs	Enhanced efficiency fertilisers[211,212]	Fertilisers that are smart controlled release and can matching the release of the nutrient to the root / plant stage.	
1	Inputs	Nanopesticides[213,214]	The use of nanopesticides to improve pest control. Any pesticide formulation intentionally including nanosized entities (up to 1000 nm) and claiming new properties arising from size are referred to herein as "nanopesticide". Nanotechnology can help mitigate the drawbacks associated with the classical pesticide formulation and application technologies.	
1	Inputs	Nanoenhancers[196,215]	Improving crop performance using nano-enhancers e.g. CuO and ZnO nanoparticles.	
2	Food processing and safety	Biodegradable coatings[177,216]	A water-, oil-, or wax-based solution applied to the surface of crops that effectively slows the rate of decomposition and maintains nutritional integrity.	
2	Food processing and safety	Microorganisms coating[177,217]	An application of micro-organisms to crops with the purpose of reducing post-harvest loss. While the goal of the application is to reduce PHL, the microbes could be distributed much earlier in preharvest processes, including on-seed, to later prevent spoilage and extend shelf life from farm to market.	http://apeelsciences.com/
2	Food processing and safety	Nanocomposites[173,218]	Nanocomposite is a very small multiphase solid material. Nanotechnology promising technology for the food packaging industry in the global market. It has proven capabilities that are valuable in packaging foods, including improved barriers; mechanical, thermal, and biodegradable properties; and applications in active and intelligent food packaging.	http://www.guard-in.com/
2	Food processing and safety	Sustainable processing technologies[219,220]	Use of sustainable, low-energy processing technologies in food processing to extend shelf life / palatability. This includes non-thermal processing technologies such as irradiation, pulsed electric fields, high hydrostatic pressure, intense pulsed lights, membrane filtration and hurdle technology. It also includes temperature-preserving packaging.	

2	Food processing and safety	Drying/ stabilisation[177,221]	Use of drying and stabilising technologies in food processing to reduce moisture content and produce a shelf-stable, nutritious dried product. These include technologies osmotic dehydration, ultrasound assisted drying, vacuum drying, freeze drying, superheated steam, drying, heat pump drying and spray drying.	
2	Food processing and safety	Whole genome sequencing[222,223]	Next generation sequencing methods represent a new toolbox that has a number of potentially transformational food safety applications, including, but not limited to whole genome sequencing. It can provide improved methods and tools to rapidly and reliably identify, detect, and predict food safety hazards.	
2	Food processing and safety	Food safety tech[224,225]	Food safety technologies are designed to provide a significant inactivation or inhibition to a microbiological population and may be used as a kill step to enhance or ensure the safety of foods. These include Microwave and Radio Frequency Electric Field (RFEF) Processing, Ohmic Heating, Infrared Heating, High Pressure Processing, Pulsed Electric Field.	
1	Gene technology	Synthetic biology[177,226]	Synthetic biology is a) the design and construction of new biological parts, devices and systems and b) the re-design of existing natural biological systems for useful purposes. Instead of cutting and editing of naturally occurring DNA sequences, synthetic biology incorporates the design and assembly of new biological entities or the redesign of existing biological systems. These new sequences can then be produced by machines at incredibly low cost using basic inputs, such as sugar. Theoretically it could allow scientists to integrate the DNA of multiple species to create entirely new hybrids.	
1	Gene technology	Novel nitrogen-fixing crops[227,228]	Develop nitrogen-fixing cereals and nitrogen fixation in crops in which it does not currently occur. An approach is to transfer the genes of legume plants necessary for the development of root nodule symbiosis to cereals. A second approach is to create nodule-independent nitrogen-fixing cereals promoting their association with endophytes that fix nitrogen. The third approach is to directly introduce nitrogenase into the plant.	
1	Gene technology	Novel perennials[229,230]	Development of temperate-adapted perennial grain legumes using gene tech/breeding - e.g. grain legumes. Development of perennial cereal grain crops through selection and breeding of wild grasses.	

1,3	Gene technology	Biofortified crops[231,232]	Biofortification is the process by which the nutritional quality of food crops is improved through agronomic practices, conventional plant breeding, or modern biotechnology. Examples of these are high amylose wheat, novel fibre wheat, gluten-free cereals, increased micronutrient contents (e.g. Zn and Fe).	
1	Gene technology	Plant phenomics[233,234]	Phenomics is an area of biology concerned with the measurement of phenomes (a phenome is the set of physical and biochemical traits belonging to a given organism) as they change in response to genetic mutation, natural and artificial selection, and environmental influences. It involves capturing information on structure, function and performance of large numbers of plants, together with their environment; analysing, organizing and storing the resulting datasets; and developing models able to disentangle and simulate plant behaviour in a range of scenarios.	
1	Gene technology	Disease/pest resistance[235,236]	Development of crops with disease and pest resistance via breeding/gene technologies. This includes development of cotton varieties with genetically modified traits for insect and herbicide tolerance and disease-resistant rice.	
1	Gene technology	Weed-competitive crops[237,238]	Develop crops that can compete better against weeds. This includes new herbicide/resistant crop combinations and new herbicides with specific targets (e.g. topical RNAi). An example is wheat varieties that can compete better against weeds, particularly herbicide resistant ryegrass.	
1	Gene technology	Genome wide selection[239,240]	Develop varieties with a higher number of desirable traits using genome wide selection. An example of this is disease resistance in wine grapes.	
1	Gene technology	Apomixis[241,242]	Apomixis (asexual reproduction through seeds) in crops to maintain key phenotypes. The introduction of apomixis—asexual reproduction through seeds—into crop plants	
1,2	Gene technology	Oils in crops[243,244]	Developing leaf and novel oils in crops using gene technology for human consumption and petrochemical replacement. Examples of this include the development of canola that contains high levels of omega-3 fatty acids in grain or plants with high concentration of oil in tissues.	
1	Gene technology	Reconfiguring photosynthesis[245,246]	Reconfiguring photosynthesis in crops. This can be achieved via a multiple pathway including bacterial transformation, nuclear transformation, plastid transformation, mitochondrial transformation, multigene	

			engineering, protein design, or synthetic genomics.	
1	Gene technolog y	Genome editing[247,248]	Genome editing used as a new tool by breeders to accelerate the introgression of favourable genetic variants for resistance, productivity and quality traits.	
1	Gene technolog y	GM assisted domesticatio n[249,250]	Genome editing used as a new tool by breeders to accelerate the domestication of semi-domesticated or even wild plants.	
1	Gene technolog y	RNAi gene silencing[251,252]	RNAi gene silencing includes both transgene driven and by topical application of RNAi molecules for regulating gene expression in crops, aquaculture and livestock species, and for control of various pests and pathogens. Gene silencing is a way of reducing, or switching off, the activity, or expression, of single genes to develop desirable traits. Examples include Safflower seed oil with high oleic acid.	
1	Gene technolog y	Genomic selection[253,254]	Genomic selection of agricultural plants and animals. This methodology has transformed the rate of genetic gain in the dairy industry and is likely to do the same for beef and plant crop species.	
1	Other	Resurrection plants[255,256]	Novel exploitation of plants that confront extreme desiccation by going into a dormant state in which they can stand losing over 95% of their water content and return to full activity upon rehydration.	
1,2	Other	Ecological biocontrol[257,258]	Integrated pest management and biocontrol. This includes reducing the number of pest or pathogens or their ability to impact food supply. Could also include increasing pollinators, and/or beneficials (predators of pests).	
3	Health	Personalised food[259,260]	Personalised food via Genetic testing, Microbiome mapping, Food on demand, Automatic personal diet supplementation, Personal nutrition status sensors, and/or Nutrigenetics.	
1	Intensific ation	Irrigation expansion[261,262]	Irrigation expansion based on massive solar panel arrays and desalination / groundwater exploitation. This includes reverse osmosis, cleaning seawater for irrigation.	
1	Intensific ation	Electro-culture[263,264]	Electricity to enhance crop growth. Bare copper wires have been suspended in greenhouses three metres above ground level. The cables run the full length of the greenhouses and carry rapid pulses of positive charge, up to 50,000 volts. These high-voltage bursts kill bacteria and viral plant diseases both in the air and the soil. They also affect the surface tension of any water droplets on the leaves of plants, accelerating vaporization.	

1	Intensification	Vertical agriculture[265,266]	Vertical farming using LED lighting (no natural light), hydroponics (no soil), aquaponics (fish), and/or air (no soil or natural light - grown on cloth with areoponic mist and LED lights), or underwater farming.	Freight Farms https://www.freightfarms.com/ Valoya http://www.valoya.com/vertical-farming/ AreoFarms https://aerofarms.com/technology/ http://www.nemosgarden.com/the-project/
1	Digital agriculture	Tracking / confinement tech for livestock[267–272]	A smart ear tag with geo-location for greater traceability and provenance of livestock and may provide a platform for other possible applications in the future.	https://www.agersens.com/
1	Digital agriculture	Pre-birth sex determination[273,274]	Pre-birth sex determination for animals such as cattle or poultry. For poultry this involves a placement of a biological marker on the chicken's sex-determining chromosome.	
1,2,3	Other	3D printing[275,276]	The use of 3D printing in the agricultural sector. This includes the 3D printing of food which involves a digitally controlled, robotic construction process that can build up complex 3D food products layer by layer.	
1,2,3	Cellular agriculture	Molecular printing[277,278]	Molecular printing techniques involves the direct transfer of molecules to a substrate with submicrometre resolution. This includes the recombination of molecular components.	
1	Inputs	Macrobials[279–281]	Macrobials and natural pest suppression is use of beneficial insects, mites and entomopathogenic nematodes as biocontrol agents and/or fertilisers. This process encourages natural predators of pest insects and reduces reliance upon pesticide control agents.	
1	Inputs	Botanicals[282,283]	The use of botanicals (e.g. bark) to replace artificial fertiliser and pesticides.	
1	Inputs	Microbials[284,285]	Development of microbial inoculum or extracts that can increase plant nutrient uptake, reduce disease incidence or stimulate growth.	https://www.pivotbio.com/
1	Inputs	Holobiomics[284,286]	Use of soil organisms to enhance ecosystem service delivery, including plant nutrition, through the promotion of soil biodiversity and targeted management of soil community composition.	
1,3	Replacement food / feed	Microalgae & cyanobacteria for food[287,288]	Replacing protein sources for humans and/or livestock with algae. Currently, microalgae and cyanobacteria are mainly sold as a dietary supplement in the form of tablets and health drinks for human consumption but are also used as feed additive for livestock an aquaculture. The main species farmed are	

			Spirulina, Chlorella spp., Haematococcus pluvialis and Nannochloropsis spp.	
1,3	Replacement food / feed	Seaweed for food[287,288]	Replacing protein sources for humans and/or livestock with seaweed. 81% of the total seaweed aquaculture production is dominated by a few species. Pyropia / Porphyra (known as "nori" in Japan) are used as human food and Gracilaria / Gracilariopsis are red algae used by the phycocolloid industry as the main source of food grade agar, but also used as animal feed.	
1,3	Replacement food / feed	Insects for food[287,288]	Replacing protein sources for humans and/or livestock with insects. Insects are currently (and increasingly) being produced for food and feed applications. They have high protein content and contain other valuable macro- and micronutrients for human diets.	
1,3	Replacement food / feed	Microbial protein[289,290]	Production of microbial protein for food, animal feed and slow release fertiliser.	http://www.solarfoods.fi/
1,3	Replacement food / feed	Livestock/seafood substitutes[288,291]	Substitutes to livestock and seafood products with same taste and texture. This includes plant based substitutes and vegetarian egg-protein meat substitutes.	
1	Replacement food / feed	Innovative aquaculture feed[292,293]	Innovative feed in used in aquaculture. An example of this is NovaCQ - bioactive aquafeed ingredient, produced via the bio-conversion of low-value plant waste from agriculture.	https://www.ridley.com.au/investors/novacq
1	Replacement food / feed	Omega-3 products[294,295]	Producing omega-3 fatty acid products from natural marine algae for all aquaculture.	https://www.veramaris.com/home.html
1	Replacement food / feed	Dietary additives for livestock[296,297]	Agents and dietary additives to improve ruminant fibre digestion and productivity and reducing methanogenesis. These include dietary lipids, electron receptors, antibiotics, enzymes in the form of cellulases or hemicellulases, probiotics (such as yeast culture), algae, propionate precursors such as fumarate or malate, condensed tannins and saponins. This includes manipulations of microbial populations in the rumen to reduce CH4 production, such as CH4 inhibitory vaccinations against methanogens or chemical defaunation to eliminate rumen protozoa.	
1,2,3	Resource use efficiency	Circular economy[298,299]	A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.	

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