Annual Review of Food Science and Technology

Building a Resilient, Sustainable, and Healthier Food Supply Through Innovation and Technology

David Julian McClements,[1] Rodolphe Barrangou,[2] Colin Hill,[3] Jozef L. Kokini,[4] Mary Ann Lila,[5] Anne S. Meyer,[6] and Liangli Yu[7]

[1]Department of Food Science, University of Massachusetts, Amherst, Massachusetts 01003, USA; email: mcclements@foodsci.umass.edu

[2]Department of Food, Bioprocessing and Nutrition Sciences, North Carolina State University, Raleigh, North Carolina 27695, USA

[3]APC Microbiome Ireland and School of Microbiology, University College Cork, Cork T12YT20, Ireland

[4]Department of Food Sciences, Purdue University, West Lafayette, Indiana 47907, USA

[5]Department of Food, Bioprocessing, and Nutrition Sciences, North Carolina State University, Kannapolis, North Carolina 28081, USA

[6]Protein Chemistry and Enzyme Technology Division, Department of Biotechnology and Biomedicine, Technical University of Denmark, DTU, DK-2800, Kgs. Lyngby, Denmark

[7]Department of Nutrition and Food Science, University of Maryland, College Park, Maryland 20742, USA

Annu. Rev. Food Sci. Technol. 2021. 12:1–28

First published as a Review in Advance on December 21, 2020

The *Annual Review of Food Science and Technology* is online at food.annualreviews.org

https://doi.org/10.1146/annurev-food-092220-030824

Keywords

future foods, food production, food processing, environmental impacts, nanotechnology, gene editing, genetic engineering, artificial intelligence, robotics

Abstract

The modern food supply faces many challenges. The global population continues to grow and people are becoming wealthier, so the food production system must respond by creating enough high-quality food to feed everyone with minimal damage to our environment. The number of people suffering or dying from diet-related chronic diseases, such as obesity, diabetes, heart disease, stroke, and cancer, continues to rise, which is partly linked to overconsumption of highly processed foods, especially high-calorie or rapidly digestible foods. After falling for many years, the number of people suffering from starvation or malnutrition is rising, and this has been exacerbated by the global COVID-19 pandemic. The highly integrated food supply chains that spread around the world are susceptible to disruptions due to policy changes, economic stresses, and natural disasters, as highlighted by the recent pandemic.

In this perspective article, written by members of the Editorial Committee of the *Annual Review of Food Science and Technology*, we highlight some of the major challenges confronting the modern food supply chain as well as how innovations in policy and technology can be used to address them. Pertinent technological innovations include robotics, machine learning, artificial intelligence, advanced diagnostics, nanotechnology, biotechnology, gene editing, vertical farming, and soft matter physics. Many of these technologies are already being employed across the food chain by farmers, distributors, manufacturers, and consumers to improve the quality, nutrition, safety, and sustainability of the food supply. These innovations are required to stimulate the development and implementation of new technologies to ensure a more equitable, resilient, and efficient food production system. Where appropriate, these technologies should be carefully tested before widespread implementation so that proper risk–benefit analyses can be carried out. They can then be employed without causing unforeseen adverse consequences. Finally, it is important to actively engage all stakeholders involved in the food supply chain throughout the development and testing of these new technologies to support their adoption if proven safe and effective.

INTRODUCTION

In 2020, The Economist reported that the food industry accounts for 10% of global GDP, with an $8 trillion global supply chain employing around 1.5 billion people (Economist 2020c). Any shock to this supply chain would therefore have devasting economic, societal, and health impacts. Moreover, this system must provide enough food for future generations. Many of the sustainability goals outlined by the United Nations are linked to the food supply: zero hunger; good health and well-being; clean water; good sanitation; and thriving industry, innovation, and infrastructure (**http://www.un.org**). The availability of a diverse range of safe, affordable, and nutritious foods is a hallmark of a prosperous society. Most of us living in developed countries take it for granted that we can walk into a supermarket or restaurant and purchase this type of food. However, for much of human history this was not the case, and it is not guaranteed that this will always be the case in the future. Indeed, the global population continues to grow, which will put increasing strain on the food supply, as we will need to feed everyone a high-quality diet while minimizing damage to our environment (Poore & Nemecek 2018, Willett et al. 2019). Moreover, as the food supply becomes more globally integrated it is important to ensure that it is resilient to economic, political, and natural shocks, as highlighted by the recent disruptions caused by the SARS-CoV-2 (COVID-19) pandemic.

This opinion piece, written by members of the Editorial Committee of the *Annual Review of Food Science and Technology*, highlights some of the most important challenges facing the modern food supply chain and indicates how recent advances in modern technology are being employed to tackle them (**Figure 1**). The application of these new technologies could have a major impact on the efficiency and sustainability of the global food supply, as emphasized in a recent report by the World Economic Forum, whose main findings are summarized in **Table 1** (WEF 2019). However, technological innovations are only one component of a broader strategy. A holistic approach is required that involves the engagement of stakeholders throughout the food supply chain, including producers, processors, distributors, consumers, educators, researchers, and regulators. In particular, new government policies, infrastructure, and investment are required to stimulate and support innovation, promote the adoption of new technologies, and inform consumers about their

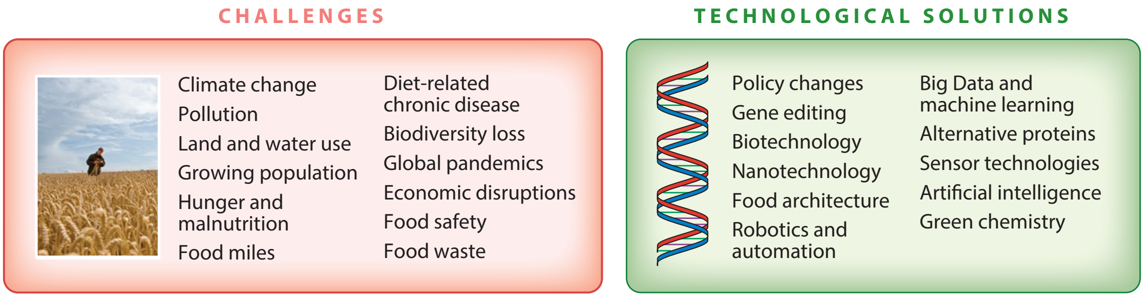

Figure 1

The modern food industry is using numerous technological innovations to address some of the major challenges associated with creating an abundant, resilient, healthy, and sustainable food supply.

Table 1 Potential economic impacts of adopting selected new technologies on the food and agriculture industry[a]

Technological innovation	Potential economic impact
Alternative proteins (plant-based, insect-based, cellular agriculture)	Reduce GHG emissions (950 million tonnes CO_2 equivalents) Reduce freshwater withdrawals (400 billion m^3) Free 400 million hectares of land
Sensor technologies (safety, quality, traceability)	Reduce food waste (20 million tonnes)
Personalized nutrition	Reduce overweight and obesity (55 million people) and other chronic diseases
Mobile service delivery (online programs and apps)	Increase farmer income ($200 billion) Reduce GHG emissions (100 megatonnes CO_2 eq) Reduce freshwater withdrawals (100 billion m^3)
Big Data and analytics (hardware and software)	Increase farmer income ($70 billion) Increase production (150 million tonnes)
Real-time supply chain transparency and traceability (IoT)	Reduce food waste (35 million tonnes)
Blockchain-enabled technology	Reduce food waste (30 million tonnes)
Precision agriculture (sowing, growing, harvesting, etc.)	Reduce farmer costs ($100 billion) Increase production (300 million tonnes) Reduce freshwater withdrawals (180 billion m^3)
Gene editing (seeds)	Increase farmer income ($100 billion) Increase production (400 million tonnes) Reduce micronutrient deficiency (100 million people)
Microbiome technologies (agricultural crops)	Increase farmer income ($100 billion) Increase production (250 million tonnes) Reduce GHG emissions (30 megatonnes CO_2 eq)
Advanced crop and soil management technologies (biologics and micronutrients)	Increase production (50 million tonnes) Reduce GHG emissions (5 megatonnes CO_2 eq)
Renewable energy generation and storage (solar, wind, water, batteries)	Increase farmer income ($100 billion) Increase production (530 million tonnes) Reduce freshwater withdrawals (250 billion m^3)

[a]Adapted from WEF (2019).

Abbreviations: GHG, greenhouse gas; IoT, Internet of Things.

potential benefits and pitfalls so they can make informed choices. Moreover, investors and donors from private companies, philanthropic organizations, and governments are needed to bring many of these technologies to fruition.

FOOD RESILIENCE AND FRAGILITY: LESSONS FROM THE GLOBAL PANDEMIC

The Problem

The COVID-19 pandemic has demonstrated both the resilience and fragility of the modern food supply (Economist 2020a,b). The majority of those living in developed countries have been able to secure most of their weekly groceries, albeit with considerably more inconvenience due to social distancing rules and panic buying of certain products (Kawamura 2020). This highlights the inherent resilience of much of the modern food supply chain: Most foods are still being produced and distributed (Economist 2020b). During the pandemic, there was still enough food to feed the entire population of the United States, although there were shortages of specific products (Vilsack 2020). Nevertheless, the pandemic has highlighted weak links and potential fragilities in the food supply chain (Vilsack 2020).

The pandemic has shuttered many restaurants, cafes, bars, and other food distribution centers, causing them to rapidly pivot from on-premise sales to electronic commerce coupled with contact-free delivery or curbside pickup (Shveda 2020). Some food production facilities, particularly meat processing factories, were forced to close because of high rates of infection caused by the close proximity of workers and strenuous working conditions (Reuben 2020, Vilsack 2020). For instance, more than a thousand cases of COVID-19 were reported from a single slaughterhouse in northwestern Germany in the summer of 2020 (Deutsche Welle 2020). These disruptions have resulted in increases in food waste and economic losses. In an interview with the BBC (Saladino 2020), Andre Laperriere, Executive Director of Global Open Data for Agriculture and Nutrition (GODAN), reported that food waste in developed economies had risen from around 30% to 40% because of the pandemic. As an example, many animals in the livestock industry could not be processed into meat because of closures of key processing facilities and thus farmers were forced to euthanize them. In the future, it may be important to have a larger number of smaller automated meat processing facilities rather than a few large labor-intensive ones that increase the risks of disruption. Similarly, many farmers were left with large quantities of unsold produce (fruits and vegetables) when supply chains broke down and restaurants and other facilities (schools, universities, and the hospitality industry) closed, leading to economic losses, increased waste (dumping of milk, meat, and fresh produce), and reduced sustainability (Kawamura 2020, Shveda 2020). These disruptions highlight the need for policy and infrastructure changes that promote the redirection of food supplies when there are disturbances in the supply chain (Kawamura 2020).

The pandemic has also constrained the cross-border transit of migrant workers who usually harvest fruit and vegetable crops and curtailed interstate and international transport of food by delivery vehicles, which has led to significant stockpiles and food waste (Park 2020). It has also led to new sanitation protocols at every link in the food production and delivery chain. It has impeded the delivery of nutritious school lunches to some of the most vulnerable. The shift of food distribution from restaurants to home consumption has necessitated changes in food packaging, portion sizes, and product labeling (Economist 2020b). Early-stage investments in food industry entrepreneurs have dwindled, and revenues for many food companies have plunged. A research analyst at Credit Suisse estimated that food-at-home spending increased to 80% of total food expenditures during the pandemic, compared to 47% before (Hensel & Kuhn 2020). The Economist magazine recently reported that the amount of food distributed by food banks in the United States had increased by more than 20%, and more than 1 in 6 children were not eating enough due to the pandemic, mainly because of the large increase in unemployment (Economist 2020a). If these high jobless numbers persist for an extended period, the nature of the foods produced by the food industry may change. In particular, there may be greater emphasis on the production of cheaper convenience foods. It will be important to ensure these foods are nutritious as well as tasty and affordable. Moreover, resources may need to be provided to families so they can afford to purchase healthy foods to feed themselves and their families (Vilsack 2020). In general, some of the poorest people in the United States and other countries were the most impacted by this crisis, and the UN predicts the number of people with acute hunger in the world will almost double to around 265 million as a result of the pandemic (Economist 2020b). It is critical to address these issues by making the food supply chain more resilient and responsive to this kind of stress.

SARS-CoV-2, although unparalleled in its impact on the food chain, follows on the heels of other infectious disease outbreaks: SARS-CoV (2002); H5N1 Avian Flu (2004); H1N1 influenza (2009); MERS-CoV (2012); and Ebola (2014, 2018). The dynamics of disease transmission, coupled with the highly interconnected nature of global food distribution systems, means it is crucial for the food industry to develop effective strategies to prevent, mitigate, and detect the effects of any future infectious outbreaks. Moreover, global pandemics, which have their own unique disruptive features (such as social distancing, reduced workforces, and unemployment), are only one potential disruption to our food supply. Other stressors, such as population growth, global warming, environmental degradation, hurricanes, volcanic eruptions, solar storms, terrorist attacks, nuclear war, economic collapse, and political factors have different effects that need to be carefully analyzed and accounted for when designing a more robust food supply chain. This will require stress tests similar to those used by the banking system.

Potential Solutions

A broad spectrum of technological innovations is being developed to address problems associated with the resilience of the modern food supply to pandemics and other disruptors. Some of the most important are briefly highlighted here.

Logistics: e-commerce and home delivery. As on-premise food services have been devastated by virus transmission fears and the need for social distancing, food deliveries and curbside pickups have skyrocketed, frequently with preordering and payment on mobile devices to eliminate currency handling and human contact. As more people become comfortable with this kind of eating experience, they may be less likely to go to supermarkets or restaurants, thereby changing how foods are purchased and consumed. Although home deliveries coordinated through online apps are convenient to consumers and help maintain social distancing, they are typically more damaging to the environment. More fossil fuels are expended in delivering small numbers of food items to individual households, and more packaging is often involved, leading to increased waste. Moreover, home delivery services are often more expensive so that only the more affluent can afford them. Some of these problems may be alleviated by using autonomous electric vehicles to deliver foods to homes (Shveda 2020) or by developing reusable or biodegradable packaging materials (see below).

Innovative e-commerce approaches are also being used by farmers to help them shift produce that could not be sold because of the disruption of their normal distribution chains. For instance, an online trading platform (iTradeNetwork) that facilitates the supply chain management of perishables has been used to link farmers to companies trying to buy or sell foods during the pandemic

(Shveda 2020). These digital services improve the quality, sustainability, and resilience of the food supply by improving freshness, reducing waste, and increasing versatility. As farmers and food manufacturers become more familiar with these technologies, spurred by the need to address disruptions caused by the pandemic, they are more likely to adopt them, thereby benefiting the food supply in the future.

Some companies have developed new digital platforms for food companies to specifically address social distancing and contact tracing within their facilities as a result of the pandemic. For instance, Proximity Trace™ from Triax (Norwalk, CT) is software developed to include a proximity alert sensor when workers get too close together, as well as keeping a record of the interactions between workers to facilitate contact tracing if a worker contracts the virus.

Robotics and automation. Many participants in the food supply chain, including raw material suppliers, food producers, and food distributors, have developed innovative means to meet the logistic challenges associated with global pandemics, many of which were inconceivable even a decade ago. As border restrictions impede the availability of migrant labor, robotic sowing and harvesting of crops are increasingly being utilized by farmers. Similarly, more food production facilities are employing robots to carry out tasks normally done by humans, such as sorting, preparing, processing, and packaging foods. In many cities under lockdown, robotic meal delivery vehicles are being utilized to circumvent face-to-face encounters. Moreover, supermarkets are removing the need for cashiers at checkout—one can already walk into some stores (such as the Amazon Go store in Seattle), select and purchase groceries, and leave without having to interact with a living person.

These trends are likely to continue after lockdown and may have a major impact on the way we produce, process, and distribute foods in the future. Many of these innovations will make the food system more efficient, improving food quality and reducing waste, but they will also have negative impacts. Many workers in the food supply chain will lose their jobs and livelihoods, which will have to be addressed through innovative policies.

Indoor farming: vertical farming. The potential for transportation disruptions along the food supply chain has spurred the development of food production facilities close to urban sites, including high-tech climate-controlled indoor farms such as vertical farming (Park 2020). Companies are looking for spaces to locate these farms in cities, such as unused parking lots, building rooftops, abandoned warehouses, underground tunnels, and even shipping containers, as well as constructing purpose-built facilities (Park 2020). These indoor farms are designed to carefully control light, humidity, nutrient, and temperature levels to optimize nutrient levels, growth, and health in crops (**Figure 2**). Initially, only high-value fruit and vegetable crops, such as herbs, spices, salad greens, and sprouts, were commercially feasible using this approach, but technological advances are leading to viability for an increasing number of other crops. These innovations will shorten supply chains and make them more resilient to disruption in the future. Indoor farming operations have numerous features that make them robust to pandemics. They typically have higher sanitation standards than conventional farms and continuously test the water supply and other inputs for potential contaminants. They involve high levels of automation and use sensors to monitor crop growth and quality, which minimizes cross-contamination and virus transmission threats.

Aerofarms (Newark, NJ) is currently the world's largest indoor research and development vertical farming operation and has already grown more than 800 different types of plants. This company was able to rapidly pivot production schedules when corporate dining and food service operations ceased at the onset of the pandemic because of the rapid growth cycles and scalable nature of indoor crop production. According to the cofounder Marc Oshima, when orders shifted from

Figure 2

Photograph of a vertical farm for growing food crops under carefully controlled indoor climate conditions. Figure reproduced with permission from Aerofarms (Newark, NJ).

on-premise dining to takeout/home delivery, the company's vertical farms were able to quickly meet the new market and supply safe, fresh, and diverse produce on demand.

Dietary strategies to support immune protection. Many people who have become acutely ill or died due to COVID-19 have compromised immune systems (Tay et al. 2020). Research shows that the ability of the human immune system to tackle infections can be enhanced through dietary interventions (Venkatalakshmi et al. 2016). As a result, researchers are trying to establish the link between specific diets, foods, and/or food components and the human immune system (Galanakis 2020). The knowledge gained from this work may lead to a new generation of functional food products specifically designed to enhance human health and resilience by strengthening the immune system. Moreover, people with diabetes, obesity, and hypertension, which can also be tackled through diet, are at increased risk of dying from COVID-19 (Nieman 2020). In particular, reducing overall calorie intake and eating more fruit and vegetables, coupled with moderate exercise, can significantly improve immune function. Current evidence suggests that a healthy diet coupled with regular exercise is a more effective primary mitigation strategy than therapeutic or pharmaceutical approaches.

Innovative food packaging and display. Foods and packaging materials are potential sources for the spread of pathogenic microorganisms, including the COVID-19 virus (Galanakis 2020). Some viruses, as well as other pathogenic microorganisms, can survive for hours or days on certain food and packaging surfaces and longer under refrigeration and frozen storage conditions, raising safety concerns for consumers as well as food service and processing personnel along the food supply chain. The ability of any virus or bacterium to survive on surfaces has consequences for the food industry. In particular, it has affected the way fresh produce is displayed, packaged, and handled. In the future, there may be fewer nonpackaged foods that consumers can directly select themselves, such as fresh fruits, vegetables, bread, and other baked products. These concerns may lead to a change to more individually wrapped foods, which could have adverse environmental consequences by increasing the amount of packaging material required. There will, therefore, be a need to develop more sustainable and environmentally friendly food packaging materials to replace plastics. Many food researchers are already working in this area and a range of innovative packaging materials have been created from more sustainable sources, such as proteins and polysaccharides found in waste streams. For instance, active packaging materials are being developed that not only provide physical protection to foods by forming mechanical barriers, controlling the flow of gasses, and screening them from harmful ultraviolet radiation but also contain natural antimicrobials that protect the foods from spoilage or pathogenic microbes (Bumbudsanpharoke et al. 2015, Sharma et al. 2020). Moreover, smart-packaging materials are being developed containing integrated sensors that provide detailed information about the freshness or safety of a food (Chen et al. 2020, Halonen et al. 2020, Pal & Kant 2020).

Alternative protein sources. COVID-19 and numerous other contagious diseases have arisen due to the transfer of viruses from animals to humans (Yuan et al. 2020). Indeed, it is hypothesized that this pandemic started due to transmission of the virus from a bat to an exotic livestock animal (possibly a pangolin) and then to humans. The close contact between animals and humans in the livestock industry may therefore promote the spread of viruses, as demonstrated by the various contagious diseases that have afflicted humans in recent decades, including swine flu (pigs), avian flu (chickens), and mad cow disease (cattle) (Yuan et al. 2020). Increasing public awareness of the risks associated with the spread of zoonotic diseases linked to livestock production may further increase interest in replacing animal proteins with nonanimal alternatives, such as those derived from plants, insects, seaweeds, or cellular agriculture (Bleakley & Hayes 2017, Fasolin et al. 2019). Many researchers are already working to identify, isolate, and purify these proteins from natural sources as well as use them to create food products that can successfully replace conventional animal-based ones, like milk, cheese, eggs, and meat (Ismail et al. 2020, McClements et al. 2019). Successful commercial products have already been created, most notably those from Impossible Foods, Beyond Meat, and Just. Nevertheless, more funding is still required from government agencies and private investors to stimulate research in this important area.

FOOD PRODUCTION AND SUSTAINABILITY

The Problem

The United Nations predicts the global population will reach nearly 10 billion by 2050 (U.N. 2019). More people are increasing their animal protein consumption through high-protein foods such as meat, fish, eggs, and milk as they become wealthier. The raising and processing of animals for food require more valuable resources (land and water) and cause more environmental damage (greenhouse gas emissions, pollution, and species extinction) than the same quantity of plant-based foods (Poore & Nemecek 2018, Willett et al. 2019). A major challenge confronting the modern food supply chain is thus feeding an expanding world population while protecting the environment.

Potential Solutions

Numerous innovative technologies are being developed to address problems associated with producing more foods, reducing food waste, and decreasing the negative impacts of food production on the environment. These innovations stretch from optimizing seeds using genetic approaches, enhancing their growth using next-generation pesticides and fertilizers, and harvesting, processing, and transporting them using autonomous machines. A few examples are provided below.

Improving food production through modern biotechnology. Modern biotechnology is being applied to agricultural practices to improve their efficiency and create new and improved products. In particular, genetic engineering has already had enormous impacts on foods produced globally and arguably has enormous potential for continuing to transform the food supply (Es et al. 2019, Kamthan et al. 2016, Murray & Maga 2016). The genes of many of the animals, plants, and microbes utilized in food production can be precisely manipulated to improve food yield, resilience, sustainability, and nutrition. Nevertheless, it is important that these genetic engineering technologies are safe, do not promote undue environmental damage, and are acceptable to consumers and regulators (Wunderlich & Gatto 2015). There is still considerable resistance to genetically modified (GM) foods, despite strong evidence that they have been successfully employed for decades without causing human health or environmental issues (Delaney et al. 2018).

There are many potential applications of genetic engineering in the food and agricultural areas, which have broadened with the advent of CRISPR-based genome-editing technologies. As an example, genetic engineering can be utilized to enhance the nutritional profile of the lipids in commodity crops, like soybeans or canola, by increasing the amount of polyunsaturated (ω-3) fatty acids they contain (Zafar et al. 2019). It can also be used to reduce food waste by inhibiting the browning of fruits and vegetables, such as apples and potatoes. This is being achieved by editing their genes to reduce the concentration of specific enzymes expressed by the plants, such as polyphenol oxidase. Indeed, commercial products are already on the market in the United States that utilize this approach to increase food quality and reduce food waste, e.g., reduced browning apples by Arctic Apples™ and potatoes by Simplot™. Genome editing is also being implemented to improve livestock (hornless cattle, leaner swine, more disease-resistant animals) as well as the microbes used in food fermentations (dairy starter cultures, brewer's yeast, and probiotics) (Doudna & Sternberg 2017).

Improving food sustainability using cellular agriculture. Cellular agriculture is another innovative biotechnology that can potentially reduce the environmental impact of the modern food production system (Mattick 2018, Waschulin & Specht 2018). Cultured or clean meat can be grown in commercial-scale bioreactors by cultivating cells isolated from a living animal within a suitable environment (Bhat et al. 2019). Typically, several cells are collected and then grown in a bioreactor containing an aqueous broth of the nutrients and growth factors (Specht 2018). The temperature, oxygen levels, and mechanical forces within the bioreactor are also optimized to stimulate efficient cell growth. Cultured meat has several potential benefits over conventional meat due to environmental, sustainability, and ethical reasons. It results in fewer greenhouse gas emissions, generates fewer pollutants, and requires less land and water than conventional meat (Alexander et al. 2017, Mattick et al. 2015). It does not promote the loss of biodiversity linked to modern livestock production. It does not involve the confinement and slaughter of huge numbers of animals, such as cows, pigs, sheep, and chickens. Moreover, it does not require close contact between animals and humans, thereby decreasing the risk of zoonotic diseases such as COVID-19. The main challenge in this area is to economically produce meat-like products on a scale that can have a substantial impact on the conventional livestock market. Nevertheless, numerous companies already claim they will be bringing cultured meat products to the market in the near future, such as Just and Memphis Meats from California (**Figure 3**).

Figure 3

Photograph of a meat product (Southern fried chicken) produced by cellular agriculture. Figure reproduced with permission from Memphis Meats (**http://www.memphismeats.com**).

Cellular agriculture is also being employed in the food industry to create functional food ingredients, such as enzymes, emulsifiers, vitamins, nutraceuticals, colors, and flavors, which are secreted by specific yeast or bacteria during microbial fermentation. Indeed, several food companies have already developed cellular agriculture processes based on specific microbes to produce proteins that are analogous to those found in meat, eggs, or milk (McClements 2019, Waschulin & Specht 2018). For instance, Perfect Day produces milk proteins, Clara Foods produces egg proteins, and Modern Meadow produces meat proteins. A gene known to code for a particular protein (such as a milk protein) is inserted into the genetic material of the microbe (Darvishi et al. 2018). The microbe is then grown in a fermentation tank under optimized conditions, which promotes expression of the desired protein, which is then isolated and purified. These cellular agriculture processes are extremely powerful because they can be used to create any protein found in nature, provided the DNA sequence needed to express it is known. In many cases, however, appreciable work needs to be done to create economically viable processing operations that can produce food ingredients on a commercially viable scale. Moreover, it is critical to overcome unfavorable consumer perceptions of genetically modified foods before these technologies can be fully accepted.

Nutrient-dense microbes, such as algae, fungi, and bacteria, suitable for human consumption can also be cultivated within bioreactors using modern fermentation methods (Ritala et al. 2017). A commercially successful application of this approach (Quorn™) involves the production of meat-like products, such as fillets, burgers, nuggets, and sausages, using a microfungus known as *Fusarium venenatum*. This microbe grows into thin filaments that somewhat resemble the muscle fibers in conventional meat products in terms of their appearance, texture, and mouthfeel (Finnigan 2011, Wiebe 2002). Other kinds of microbes also have potential as meat replacers and are being investigated for this purpose (Fasolin et al. 2019, Ritala et al. 2017).

Reducing food waste through biotechnology. Currently, as much as 30–40% of the food produced globally is wasted, thereby losing valuable nutrients and resources. Innovative biotechnology approaches are being developed to reduce waste and enhance economic value by upgrading food processing sidestreams (Lange & Meyer 2019). Valorization of sidestreams from many classic large-scale food processes such as beer brewing, cheese production, and meat processing has become vital to increasing competitiveness and sustainability. These biorefinery processes are being used to create novel functional food ingredients from a variety of sidestreams by carrying out controlled microbial or enzymatic transformations (Lange & Meyer 2019). Some of these sidestreams are also being used as resources to create innovative biodegradable food packaging materials to reduce the negative impacts of plastics on the environment (Kabir et al. 2020, Sirohi et al. 2020). Overall, these technologies have the potential to create new jobs, reduce waste, decrease pollution, and provide healthier and more sustainable foods.

Enhancing agricultural efficiency using nanotechnology. Nanotechnology involves the creation or manipulation of materials on the nanoscale (1–100 nm) to introduce new or improved physicochemical properties (Khot et al. 2012, Sozer & Kokini 2009). The functional attributes of materials often change considerably when their dimensions are reduced to the nanoscale, leading to innovative approaches to improve food production processes. Nanotech is being utilized to create nanofertilizers and nanopesticides that have benefits over conventional varieties (Adisa et al. 2019). For instance, the tiny dimensions of nanoparticles allow them to penetrate into plants more readily than larger particles. As a result, they can exhibit their desired functions more effectively, e.g., by providing nutrients to the plants or by destroying internalized plant pathogens. A new generation of nanoenabled pesticides and fertilizers would increase yields, decrease waste, improve quality, and decrease pollution.

Functionalized nanoparticles are also being employed as minuscule diagnostic tools to generate data about the growth stage or health status of plants, the quality of the surrounding soil, or the environmental conditions to which the plants are exposed (Kamle et al. 2020, Usman et al. 2020). Water filters containing nanofibers have been developed to remove contaminants or nutrients from wastestreams arising from agriculture production, thereby reducing pollution and creating new resources (McClements 2019). They have also been used to desalinate seawater, thereby increasing the amount of water available for agricultural applications (Saleem et al. 2020). Research is being carried out to assess the potential impact of any nanoparticles used in the food supply chain on human and environmental health (Jain et al. 2018, Kaphle et al. 2018).

Digital building blocks: Big Data, artificial intelligence, and machine learning. Our ability to efficiently produce and distribute foods can be optimized by generating more detailed and comprehensive information about their properties along the entire food chain and then rapidly acting upon this knowledge (McClements 2019, WEF 2019). Innovative sensor technologies are being created to obtain data about specific food attributes (such as composition, quality, freshness, and microbial contamination) and the factors impacting them (such as temperature, humidity, light, and oxygen levels). As an example, the growth stage and health status of agricultural crops and the soils that nourish them can be monitored using tiny sensors embedded in or near the plants so that water, fertilizers, and pesticides can be applied at the precise time they are required, as well as enabling harvesting at the optimum time (Shafi et al. 2019). This kind of precision agriculture can treat each plant individually according to its specific needs, thereby increasing yields and reducing waste.

Sensors are already available that generate data about the environmental conditions that agricultural crops or food products encounter as they are harvested, stored, processed, and distributed, including factors such as variations in temperature, light exposure, relative humidity, and mechanical stress (Thakur et al. 2019). These sensors are often integral parts of autonomous machines (such as tractors or combine harvesters) or drones that can both monitor and treat crops (Maes & Steppe 2019, Thakur et al. 2019). The multitude of data points generated by these sensors can then be used to build comprehensive data sets that relate important food or agricultural attributes (quality, safety, and shelf life) to environmental conditions. This information can then be used to optimize food quality, increase food safety, and reduce food waste by optimizing the conditions the products experience throughout the food chain, from farm to table. Advances in computer science, such as artificial intelligence, machine learning, the Internet of Things, and blockchain technology, provide powerful tools to establish these relationships (Akyazi et al. 2020).

Advanced robotics and autonomous machines. Advanced autonomous machines, such as tractors and combine harvesters, are being increasingly used to sow, cultivate, harvest, and process agricultural commodities, which is leading to major enhancements in the efficiency and productivity of farming practices (Wilde 2020). These machines typically contain advanced sensor technologies and a global positioning system (GPS) so they can collect detailed localized information about crops and environmental conditions. The precision harvesting market is reported to be growing at an annual rate of around 11% and is expected to reach around $17.5 billion by 2024 (Claver 2019, MarketsandMarkets™ 2019). The market for these autonomous farming machines is increasing in both developed and developing countries and includes hardware, software, and services. As well as improving farming efficiency, robotic farm machinery also makes the food supply less susceptible to labor shortages and pandemics. Thus, the more widespread application of these advanced technologies should lead to better quality and more nutritious foods while decreasing energy costs and food waste. These new technologies are relatively expensive and thus are currently out of reach of millions of subsistence farmers around the globe. If more of these advanced farming practices can be adopted globally, then the quantity and quality of food available to those who most need it will increase. This will require increased investment by governments, philanthropic organizations, and businesses as well as innovations in policy (WEF 2019).

Increasing sustainability through innovative indoor farming methods. The potential for innovative indoor farming practices, such as vertical farming, to improve the resilience of the food industry was discussed above. However, indoor farming may also have a pronounced impact on the sustainability of food production (O'Sullivan et al. 2019). The supply chain for many food products is extremely long, often stretching around the globe. The distribution of foodstuffs across large distances involves substantial use of fossil fuels to transport and store the food. The majority of food consumption occurs within large urban centers; thus, it would be advantageous to bring food production facilities closer to cities and towns to shorten food supply chains. Several technologies are being developed to achieve this goal, including advanced climate-controlled greenhouses, hydroponic or aeroponic operations, and vertical farming (Shamshiri et al. 2018). These innovative farming approaches have become increasingly economically viable due to technological advances and concerns about potential disruptors of the food supply, such as immigration issues, border controls, land and water resource conservation, contamination concerns, and transportation disruptions.

Vertical farming operations typically cultivate plants in nonsoil substrates in trays stacked in vertical tiers that have specialized equipment to deliver water and nutrients at appropriate times and levels (**Figure 2**). The plants are exposed to artificial light-emitting diodes, and the light spectrum (intensity versus wavelength profile) can be fine-tuned to optimize growth and enhance nutritional quality. Vertical farms typically involve high levels of automation to plant, maintain, and harvest crops, as well as sophisticated sensor technologies and computational methods to collect and analyze data. This information can then be used to optimize growing and harvesting conditions. Minimal (or no) pesticides are required during the indoor production cycle. The traceability of the food supply is far superior, in that a plant food source can be traced back to the square inch or the seed if needed. The growing period for produce is drastically reduced in vertical farming, allowing production runs to quickly adapt to changing demands. Moreover, vertical farms are much less susceptible to changes in climate, which will be important as outdoor growing conditions are affected on conventional farms by climate fluctuations. Finally, vertical farms are typically situated close to urban markets and are able to supply local greengrocers with minimal carbon footprint products, as the produce does not require much transit or extended storage conditions. For instance, a vertical farm jointly operated by CropOne (based in California) and Emirates Flight Catering produces greens for Dubai's airport and reports 99% less water consumption than conventional production.

Improved sustainability through alternative proteins. Scientists are currently identifying alternative sources of proteins that can be incorporated into the human diet, such as those arising from plants, insects, microbes, and tissue cultures. Indeed, one of the most widely publicized applications of modern food technology has been the creation of plant-based meats. The plant-based burgers created by companies such as Impossible Foods and Beyond Meat in the United States have been a huge commercial success. The complexity of the science behind their creation, however, is often unappreciated. The assembly of plant-based ingredients, such as the proteins from peas or soybeans, into something that looks, smells, tastes, feels, and even sounds like meat is truly remarkable (**Figure 4**). The muscles, connective tissue, and adipose tissue of animals consist of specific molecules organized into highly complex hierarchical structures. Making meat-like structures from plant proteins and other ingredients required understanding their properties at

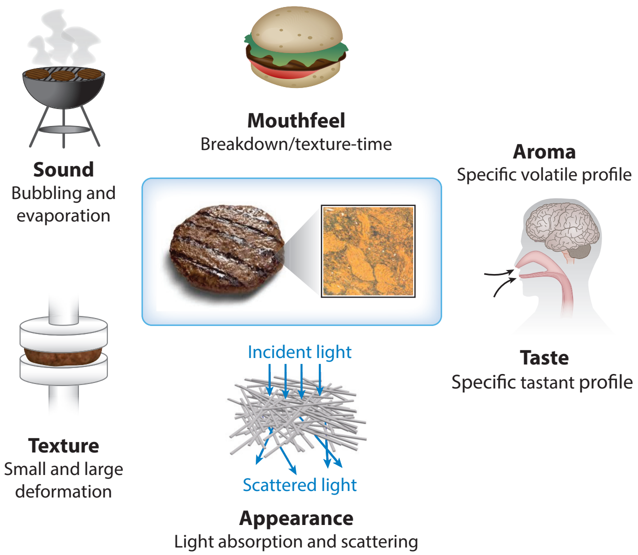

Figure 4

Structural design principles have been used to create plant-based foods that mimic the desirable sensory, physicochemical, and rheological properties of traditional animal-based foods, such as burgers.

a fundamental level and involved years of work involving food chemists, physicists, biologists, engineers, and sensory scientists.

Scientists are also developing microbial- and insect-based products to replace meat (Akhtar & Isman 2018, van Huis & Oonincx 2017). Many of these alternative protein sources have fairly comparable nutritional profiles, such as macronutrient and micronutrient levels, to meat. Nevertheless, a great deal of technological knowledge is still required to economically and sustainably produce them at the scale required to replace conventional meat, as well as to convert them into products that people find desirable.

FOOD AND HEALTH

The Problem

Even when there is sufficient food to feed all the people on the planet, there are still problems associated with the type and amount of food consumed (McClements 2019). In both developed and developing countries, there are large segments of the population who suffer from hunger and malnutrition because they do not have access to affordable high-quality foods. At the same time, there are other segments of the population who suffer from chronic diseases related to the consumption of too much food or the wrong types of food. As an example, deaths from heart disease, cancer, obesity, and diabetes continue to increase (**Figure 5**), many of which can be attributed to poor diet and a lack of physical activity. Technological innovations may be able to improve the nutritional value of foods to tackle both undernutrition and overnutrition.

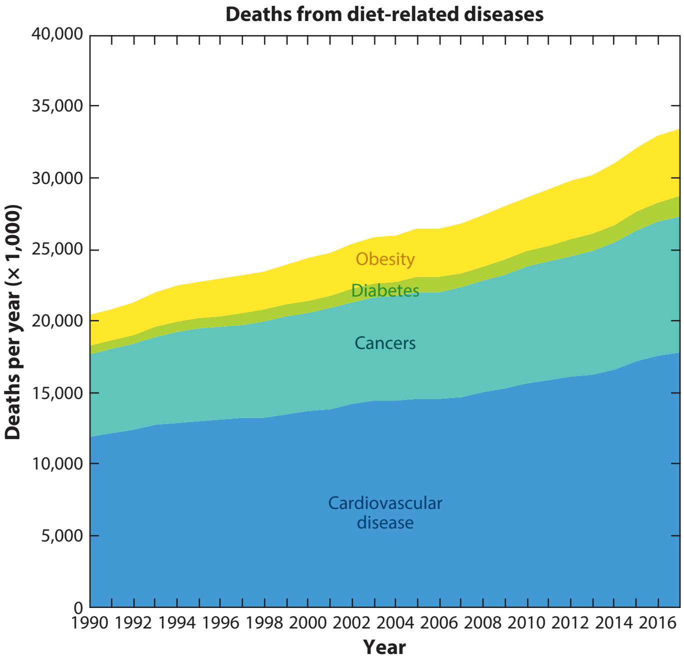

Figure 5

The deaths from diet-related diseases continue to increase globally. Data from Our World in Data (**http://www.ourworldindata.org**).

Potential Solutions

In this section, some technological solutions are discussed that are being developed to improve the healthiness of the food supply.

Reducing malnutrition. There are still many people around the globe who suffer from severe hunger and undernutrition, often a result of poverty, war, or political/economic disruptions. Solutions to these crises typically require action by governmental or international agencies aimed at addressing political or economic issues. Even so, technological innovations can help address some of these challenges by increasing the efficiency of food production, storage, and transport. Genetic engineering can create crops that are more resilient to environmental changes, produce higher yields, enhance nutritional quality, or reduce losses (Altpeter et al. 2016). Automated (robotic) farming technologies can increase the efficiency of food production (Wilde 2020). Modern sensor technologies and data storage/analysis techniques collect and share information that can be used to optimize production conditions (Pal & Kant 2020). For example, information about soil conditions, climate, and plant health and growth stage can be used to identify optimum seeds, fertilizers, pesticides, application times, etc. Food design approaches can be used to fortify foods with essential micronutrients (vitamins and minerals) and increase their bioavailability, which can help alleviate malnutrition due to nutrient deficiencies. For instance, creating nanosized versions of oil-soluble vitamins, such as vitamin A, D, or E, can increase their bioavailability and therefore health benefits (Katouzian & Jafari 2016).

One of the major problems in this area is that many of the technologies are too expensive for the populations that need them. Consequently, it will be important for government and industry to develop cost-effective strategies to ensure these technologies are implemented in a way that can benefit the people most in need. Moreover, there is often resistance to the adoption of new technologies from both local populations and nongovernmental organizations, as demonstrated by the resistance to genetically modified fortified crops (such as Golden Rice).

Reformulating dietary composition to improve health. For most of the world's history, the majority of humans suffered from chronic conditions linked to eating too little food. According to the World Health Organization, there are now more people dying from chronic conditions linked to overeating (such as stroke, obesity, diabetes, and heart disease) than to undereating (starvation and malnutrition). As an example, data for the main causes of death in the world in 2017 are shown in **Figure 5**. Many of the most common causes of death (stroke, obesity, diabetes) are a result of diet-related factors, such as high levels of calories, fat, sugar, or salt in the diet, or low levels of whole grains, fruits, vegetables, nuts, seeds, and ω-3 fatty acids. There has therefore been an effort to reformulate foods to improve their nutritional profile, with an aim to increasing their healthfulness.

Obesity and diabetes have been linked to overconsumption of calorie-rich high-fat and high-sugar foods, like breads, cakes, candies, cookies, and snacks (Gibney et al. 2017, Hruby & Hu 2015, Mozaffarian 2016). Consequently, there has been a drive to develop reduced-fat and reduced-sugar versions of conventional foods so as to reduce their energy density (Chung et al. 2016, Jaenke et al. 2017, Kroger et al. 2006). This is often challenging because fats and sugars play a critical role in determining the desirable appearance, texture, and flavor of many foods. Once removed, consumers do not find the healthier versions as appealing, so they do not purchase them. Research is therefore being carried out to establish the molecular and physicochemical basis of food deliciousness, which requires a combination of fundamental physical, rheological, chemical, biological, sensorial, and psychological methods (McClements 2019). Foods are extremely complex materials comprising multitudes of different constituents assembled into complicated hierarchical

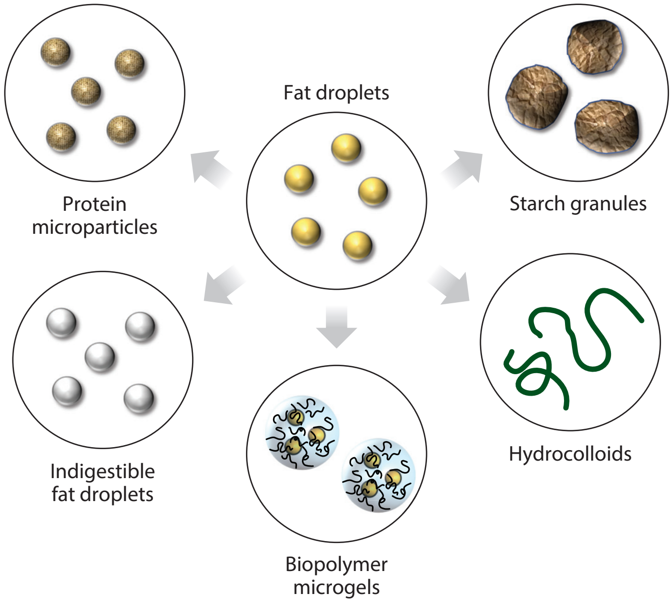

Figure 6

Schematic representation of fat droplets and starch granules and some of the strategies that can be used to mimic their properties in foods.

structures. Understanding their properties is extremely challenging, which often makes it difficult to create high-quality reduced-calorie alternatives to conventional foods.

As a specific example, consider the impact of fat droplets on the properties of high-calorie emulsified food products, such as condiments, creams, dressings, fillings, and sauces. The fat droplets scatter light waves, modulate fluid flow, and solubilize flavors, which contributes to the desirable creamy appearance, texture, and taste of emulsified foods. It is difficult to find low-calorie ingredients that can replace all the desirable characteristics of fat droplets. Some potential food-design approaches that have been developed, such as those for dietary fibers, starch granules, protein microparticles, and microgels, are highlighted in **Figure 6**. These nonfat particles can often mimic some of the desirable characteristics of fat droplets, such as their appearance or texture, but not all of them. Clearly, more research is required to reformulate many processed foods to make them both healthy and delicious, which will require a much more detailed understanding of the complexities of food architecture and the interaction of foods with the human senses.

Modulating food digestibility. A recent randomized clinical trial compared the impact of the degree of processing on the health impact of foods (Hall et al. 2019). Subjects were given either ultraprocessed foods or nonprocessed foods, which were matched for overall calories, energy density, fat, protein, carbohydrates, sodium, and fiber. The subjects consuming ultraprocessed foods tended to eat more and put on more weight than those on the nonprocessed diet. The authors concluded that limiting the amount of ultraprocessed foods consumed may therefore help prevent obesity.

The results of this study suggest that the extent of food processing has a major impact on the way foods behave in the human body. In particular, highly processed foods tend to be rapidly digested and absorbed, which alters metabolic and hormonal responses. Repeated consumption of highly processed foods may eventually lead to metabolism dysregulation, thereby leading to chronic diseases such as obesity and diabetes. It may lead to spikes in blood sugar or lipid levels and reduce feelings of satiety and satiation, hence promoting overeating. Food scientists are therefore trying to develop a new generation of processed foods that taste delicious but are chewed and digested more slowly, thereby preventing the problems associated with the rapid release of sugars and lipids from foods (Gibney et al. 2017).

The diet of our ancient ancestors consisted mainly of foods that were raw or only slightly processed, including grasses, seeds, nuts, berries, root vegetables, eggs, fish, and animal flesh (Standage 2009). These foods contain intact biological structures, such as plant cell walls, which must be broken down inside our guts before the nutrients can be released (Holland et al. 2020). The human gastrointestinal tract has therefore evolved structures and functions that are efficient at breaking down these tough natural structures, such as teeth, acidic gastric juices, a churning stomach, digestive enzymes, and bile salts. In ancient times, most foods consumed by humans were broken down relatively slowly, but in modern times ultraprocessed foods are rapidly digested and absorbed within our guts. This is because food processing operations are highly efficient at disrupting the natural structures in foods.

Researchers have therefore focused on the development of strategies to retard the digestion of processed foods within the human gut, particularly lipids and starches (Grundy et al. 2016). This can be achieved by using both food processing and food design approaches. For instance, food processing operations are being redesigned to leave many of the natural structures in foods intact so that they slow down the digestion of fats and starches. As an example, whole-grain breads are digested more slowly than highly processed white bread because the starch is trapped inside natural protective structures that prevent the digestive enzymes from reaching it (Scazzina et al. 2013). Alterations in food manufacturing processes are also being used to change the molecular organization of the starch molecules in foods so that more is available in a slowly digestible or resistant form (Ashwar et al. 2016). Starch digestion and absorption can also be reduced by incorporating dietary fibers into foods, which are designed to inhibit the ability of digestive enzymes from reaching the starch molecules (Gidley 2013, Williams et al. 2019). Dietary fibers may achieve this by increasing the viscosity of the gastrointestinal fluids, binding to digestive enzymes, or creating protective barriers around starches (Capuano 2017, Gidley & Yakubov 2019). The activity of digestive enzymes may also be reduced by incorporating natural substances, such as plant polyphenols, in foods that bind to them and inactivate them (McDougall & Stewart 2005, Xiao et al. 2013). Similar approaches can be used to inhibit the digestion of fat in the gut, thereby preventing spikes in blood lipid levels (Joyce et al. 2016, McClements et al. 2009). Many of these structural design approaches are still being developed and tested in research laboratories, and further research is required to ensure they are efficacious under real conditions. Nevertheless, this research may lead to a new generation of processed foods that are affordable, delicious, and convenient but also healthier.

Food as medicine. Functional foods contain one or more bioactive components that are claimed to improve human health, such as vitamins, minerals, nutraceuticals, dietary fibers, and probiotics. It has been reported that there were nearly $267 billion in sales of fortified and functional foods in 2020 (Sloan 2020). There has also been growing interest from consumers in improving their health by taking dietary supplements containing bioactive components. For instance, approximately 77% of adults in the United States used dietary supplements in 2019, with total supplement sales of around $49.3 billion (Sloan 2020). Consumers are increasingly looking for specific health benefits from functional foods and dietary supplements. As mentioned earlier, there has been interest in foods that can boost the immune system to create resilience against viral and bacterial infections.

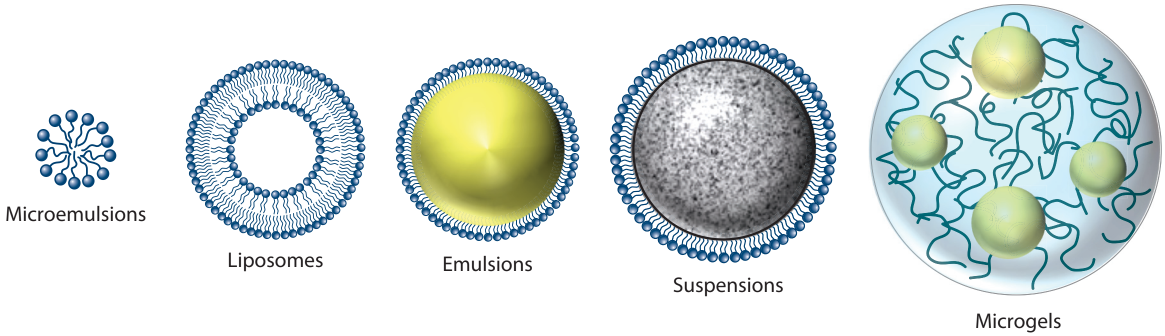

Figure 7

Examples of colloidal delivery systems that can be used to encapsulate, protect, and deliver nutraceuticals in foods and beverages. Emulsions contain fluid droplets, whereas suspensions contain solid particles (McClements 2015).

At present, this field is still in its infancy and many of the claims made for the health benefits of different food components have not been validated. Multidisciplinary collaborations involving food science, nutrition, pharmaceutical science, cellular and molecular biology, chemistry, toxicology, computational methods, and statistics are still required to further develop this field and establish the efficacy of different bioactive components.

Functional foods fortified with essential minerals, vitamins, nutraceuticals, and dietary fibers must be carefully designed to ensure that these health-promoting ingredients do not negatively impact their quality attributes (Gupta 2016). Many bioactive ingredients may be difficult to incorporate because of their incompatibility with the food matrix, their tendency to degrade during storage, their undesirable aromas, tastes, textures, or appearances, or their poor bioavailability (Zhang & McClements 2016). For these reasons, food scientists are developing structural design principles to fortify foods with bioactive agents. For instance, nanotechnology is being used to create a new generation of fortified foods and beverages with enhanced health benefits (Salvia-Trujillo et al. 2017). Edible nanoparticles are being assembled from food-grade ingredients such as fats, proteins, and carbohydrates (**Figure 7**) (McClements 2015). Bioactive components like vitamins, minerals, and nutraceuticals are then packaged inside these nanoparticles to improve their food compatibility, stability, and bioavailability.

Improving gut health through food design. Traditionally, dietary and nutritional advice has been targeted at the human host, with the main objective being the provision of their macronutrient and micronutrient needs. Our increasing understanding of the role of the microbiome in human health and disease is leading to a revolution in nutritional sciences (Liang et al. 2018). In the future, diets will be specifically designed to create and maintain a diverse and resilient microbiome. At its simplest, this will involve the inclusion of nondigestible carbohydrates such as dietary fibers or prebiotics to encourage the development of already established beneficial bacteria such as *Bifidobacterium* and certain *Faecalibacterium* spp. (Azcarate et al. 2017). However, as evidence continues to emerge linking commensal bacteria to beneficial health outcomes, we can expect to see more foods and smart ingredients designed to encourage the establishment of these beneficial bacteria in the gut. For example, diminished levels of *Faecalibacterium prausnitzii* in the gut have been linked to inflammatory bowel disease (Cao et al. 2014), whereas low levels of *Akkermansia muciniphila* have been associated with metabolic syndrome (Depommier et al. 2019). It is likely that personalized diets will be based on not only the nutritional needs of the host but also the specific composition of the gut (and other) microbiome of every individual. Infant formula will also be formulated to mimic the beneficial effects of human breast milk on the developing microbiome, with long-term effects on the health of the developing infant (Stewart et al. 2018). This will be particularly important in infants born by caesarean section (Shao et al. 2019), an increasing phenomenon in high-income countries.

Recent advances in genome-editing technologies are opening new avenues to improve the genetic profile of probiotics, further enhance functional features of interest such as the ability to uptake and catabolize undigestible carbohydrate and fibers, modify their propensity to influence the host immune system and related inflammation, alter their cell-surface composition to increase binding to epithelial cells lining the gastrointestinal tract, and change their metabolic potential to modulate gut biochemical composition (Doudna & Sternberg 2017). For instance, efforts are underway to alter bile-salt hydrolases in probiotic *Lactobacillus* strains to modulate the bile-acid pool and promote a healthier microbiota composition by fending off pathogenic bacteria such as *Clostridioides difficile* (Foley et al. 2019). These approaches have the potential to complement and perhaps even provide alternatives to antibiotic-based therapeutic strategies. Together with recent developments in using programmable CRISPR-Cas systems as sequence-specific antibacterials (Selle et al. 2020), a series of innovative technologies provide new means to modulate the bacterial composition of the gut microbiome and further improve intestinal health.

Personalized nutrition. The concept of personalized nutrition is that diets should be tailored to the unique nutritional requirements of a specific individual according to their needs rather than general populations (Bordoni & Gabbianelli 2019, Gonzalez-Pena & Brennan 2019). The nutritional needs of an individual depend on their lifestyle, age, sex, genetics, metabolism, and microbiome. As a result, a young male with obesity requires a different diet than an older female with diabetes. The possibility of designing diets for specific individuals has arisen because of important technological advances in genetics, metabolism, diagnostics, computation, and data analysis (Eetemadi et al. 2020, McClements 2019). Food, nutrition, and medical scientists can now quantify the multitudes of molecules and microbes found in foods as well as those present in human biological samples, including blood, saliva, urine, and feces. As an example, alterations in the levels of specific metabolites and microorganisms inside people when they are exposed to different foods can be measured. This knowledge is then utilized to link diet, genetics, metabolism, lifestyle, and health (Bordoni & Gabbianelli 2019). Eventually, it should be possible to formulate diets that are tailored to the specific nutritional and health requirements of each person.

Personalized nutrition requires that functional foods are created with specific nutrient, nutraceutical, prebiotic, and probiotic combinations (Braconi et al. 2018, de Toro-Martin et al. 2017, Ozdemir & Kolker 2016). In some cases, these bioactive ingredients can simply be mixed into a food matrix, but in other cases they need specialized encapsulation technologies to disperse and protect them and increase their bioavailability. Many of the encapsulation technologies discussed earlier can be used for this purpose (**Figure 7**). As an example, oil-soluble vitamins (vitamin A, D, and E) and nonpolar nutraceuticals (like carotenoids, curcumin, and resveratrol) can be incorporated into delivery systems that contain small hydrophobic particles (like nanoemulsions or emulsions) to enhance their water dispersibility, chemical stability, and oral bioavailability (McClements 2015). Single or multiple bioactive agents can be packed into a single delivery system according to their physicochemical and nutritional attributes

FOOD SAFETY

The Problem

The next few decades will create significant challenges in terms of food safety. Longer food supply chains, novel food sources, new processing technologies, consumer desires for minimally processed foods with fewer additives (so-called clean-label foods), the rise in demand for fresh, natural, and organic foods, and the potential emergence of new pathogens are all likely to become obstacles on the path to delivering a safe, reliable, and economically viable food supply. In the future, food scientists will have to continue to deliver safe foods under challenging circumstances. However, this is not new territory. The quest to deliver safe food has always had to adapt to new challenges: The need for sufficient food to supply armies traveling long distances led to the development of canning; providing safe food for space missions gave rise to Hazard Analysis Critical Control Point (HACCP) analysis; and modified atmosphere packaging owes its origins to the challenges associated with transporting meat from Australia and New Zealand to Britain in the 1930s. We can expect that new challenges will lead to innovative new solutions that may become widely adopted in the food industry in the future. For example, genetically modified foods may be designed with built-in safety features, such as crops that are designed to produce their own endogenous food-grade antimicrobial peptides or metabolites.

Potential Solutions

Mapping the future direction of food safety is not an easy task, but we can make some predictions under several headings, including processing and risk assessment, ingredient development, traceability, and novel detection methods.

Food processing and risk assessment. There have been many innovations in terms of food processing, including high-pressure processing (HPP), pulsed electric field (PEF), sonication, irradiation, and cold plasma technologies, to name a few (Bevilacqua et al. 2018, Jambrak et al. 2018, Morales-de la Pena et al. 2019). These technologies have mainly been developed to avoid some of the undesirable losses in nutritional and sensory attributes caused by traditional thermal processes while conferring increased safety and shelf-life on the foodstuff. Many of them also have lower energy requirements and are more sustainable. The ability of these technologies to destroy pathogens has been investigated to varying degrees (Bahrami et al. 2020). Currently, many food safety assessments are conducted by deliberately introducing specific pathogenic strains (or strain mixes) into model systems and then exposing them to well-defined processing stresses. We can expect that much of the risk assessment in the future will be performed computationally rather than by traditional microbial spiking and counting methods. We can confidently predict that our growing understanding of the complete genome complement of pathogens will provide us with comprehensive and accurate models of bacterial behavior under almost any stress or normal condition. These models will predict the fate of any pathogens present in a food given information about its structure and composition and the nature of the processing conditions it experiences. Similar models will predict the fate of the other microbes likely to be present in a raw foodstuff and throughout the food chain (the food microbiome) (McHugh et al. 2020), giving us the potential to eliminate pathogenic microbes while retaining beneficial ones. This should support and accelerate our ability to design and develop new processing modalities while retaining confidence in the safety of the food supply.

Detection methods. Molecular detection methods based around multitarget PCR technology and/or other nucleic acid–based detection methods will become central to food monitoring (Randhawa et al. 2016). This will include real-time sequencing of food samples using technologies based on nanopore sequencing protocols (Yang et al. 2020). This will give instant readouts on the number and nature of the microbes present within a sample that can be used to inform retail and consumption decisions. These highly sensitive and rapid diagnostics will probably be pioneered in the clinical sciences but will quickly move into the food chain. We can also anticipate the development of smart labels that will detect volatile microbial metabolites, thereby monitoring microbial activity within food products and giving real-time readouts on their safety and quality rather than relying on prescribed shelf life and "best before" labels that can lead to large quantities of food being discarded unnecessarily. Indeed, smart-packaging materials have already been developed that provide information about the freshness of meat and seafood, which are simply based on changes in the color of the packaging in response to the formation of volatiles produced by spoilage organisms (Dong et al. 2020).

Food traceability. The origin and history of a food are likely to play an increasingly important role in consumer food choices in the future. Consumers want to know where their foods came from as well as how they were transported, processed, and stored so they can assess their safety, quality, nutritional profile, and sustainability. This will require the development of innovative technologies to track and record the history of individual food products and then provide the consumer with access to the information in an accessible form. Several companies have already developed technologies that consumers can use to scan the label of a product and obtain information about its nutritional value (Maringer et al. 2019). Some supermarkets in the Netherlands now provide customers with the opportunity to obtain detailed information about the origin of a product and the journey it took to reach the shop by simply scanning a Quick Response (QR) code on its label (Gibson 2019). For instance, a person can pick up a bottle of orange juice on a supermarket shelf and see images of the orange grove it was picked from and how it was transported across the globe.

Next-generation natural antimicrobials. Traditionally, many of the antimicrobials used to preserve foods were naturally produced from lactic acid bacteria such as bacteriocins (e.g., nisin), organic acids (e.g., lactate, propionate, acetate), and citrus fruits (e.g., citrate). Efforts to improve on natural preservatives were formulated from genetic selection and engineering (Field et al. 2015) and production of synthetic chemicals (Davidson et al. 2020). However, because of consumer concerns about the potentially negative health and environmental impacts of these substances, there has been growing interest in developing natural antimicrobials (Quinto et al. 2019). Bacteriocins and bacteriophages have already been successfully deployed in the food industry, and their mechanisms of action are well understood (Aziz & Karboune 2018, Garcia et al. 2010, Singh 2018). There has also been great interest in essential oils and other phytochemicals that exhibit strong antimicrobial activity (Rao et al. 2019). These substances are often secondary metabolites developed by plants to protect themselves from microbes, insects, or herbivores (Wink 2003). Essential oil nanoemulsions have been shown to be effective against various types of spoilage and pathogenic organisms found in foods (Donsi & Ferrari 2016). These formulations consist of tiny essential oil–rich droplets ($d < 200$ nm) dispersed in water. The small size of the droplets facilitates their ability to interact with the surfaces of microorganisms. The mechanisms of action of these chemical antimicrobial agents are still being investigated. However, it is mainly believed that these constituents disrupt cell membranes and interfere with key components, such as enzymes, transcription factors, signaling molecules, and transporters, in the biochemical pathways that microbes need to survive and reproduce (Rao et al. 2019).

In the future, more attention will likely be given to developing both more effective broad-spectrum antimicrobials (e.g., bacteriocins) and selective antimicrobials (e.g., phage and synthetic preservatives) that eliminate a particular pathogen without destroying other members of the natural food-supported human microbiome that may be beneficial to health.

Nontargeted detection techniques. In the modern food supply, raw materials, ingredients, and finished products are transported around the world as part of a highly integrated global supply network. Food purchasers and consumers are therefore vulnerable to economic fraud and adulteration, e.g., suppliers claiming a product is something that it is not. Moreover, foods are susceptible to inadvertent or deliberate contamination with toxic substances throughout the food chain. Consequently, it is important to have analytical tools that can rapidly and reliably detect adulteration or contamination. Conventional targeted-detection techniques are designed to identify compounds with known chemical structures, which usually involves calibrating instruments with standard compounds so as to carry out qualitative and/or quantitative analyses (Gao et al. 2019). These methods can be utilized to detect known food components but are not particularly useful in detecting food adulteration or contamination with unknown substances. In contrast, nontargeted detection methods do not measure a specific compound but detect abnormal substances that may be present in a sample without needing to know their chemical structures beforehand. Nontargeted methods generally involve detection of "fingerprints" using well-established analytical instruments such as chromatography (high-performance liquid chromatography and gas chromatography), spectroscopy (infrared, Raman, fluorescence, and nuclear magnetic resonance), mass spectrometry, and hyperspectral imaging, followed by analysis using advanced chemometric, bioinformatic, or statistical data-processing techniques (Gao et al. 2019). Nontargeted detection techniques can differentiate berries obtained from different cultivars and growing locations (Lu et al. 2014), nonmilk proteins from milk proteins (Lu et al. 2015), and organically grown oregano from its conventionally produced counterpart (Gao et al. 2014). Gao and colleagues (2019) have recently reviewed other applications of nontargeted detection approaches.

CONCLUSIONS

Technological advances are occurring in many areas of science that are rapidly impacting how our foods are being produced, distributed, and consumed (McClements 2019, WEF 2019). Scientists from a broad spectrum of disciplines are contributing to these advances. The application of these technological innovations is being employed to tackle urgent challenges facing the modern food supply, such as feeding an expanding world population while minimizing environmental impacts, reducing the incidences of diet-related diseases, and improving the safety, quality, resilience, and diversity of the food supply (Poore & Nemecek 2018, Willett et al. 2019). Starting with the industrial revolution, the food manufacturing industry has successfully produced a diverse range of affordable, convenient, and delicious foods. However, the impact of these foods on human health and the environment has often been ignored. Looking forward, it will be critical for food science and technology to focus on improving the nutritional and sustainability aspects of foods. This will require pronounced changes in the way food scientists work in academia, government, and industry. In addition, modern food science will benefit from researchers working in other disciplines utilizing their unique perspectives and expertise to tackle these critical issues, including agricultural scientists, nutritionists, computer engineers, biotechnologists, polymer scientists, nanotechnologists, genetic engineers, medical professionals, psychologists, and consumer scientists. In a recent report, the World Economic Forum highlighted the huge potential that new technologies have to transform the global food supply but also noted that the food industry has been relatively slow to harness the power of these technologies (WEF 2019). Indeed, they estimate that the investment in start-ups in food and agriculture was less than 10% of that in healthcare. There is, therefore, still an urgent need for more innovation in the food sector, as well as fantastic opportunities for those who would like to invest in this area.

In summary, a holistic approach will be required to address the current challenges to the global food system so that we can produce safe, nutritious, abundant, and affordable foods in a sustainable manner. As stressed in the World Economic Forum report (WEF 2019), this will require "improved policy, increased investment, expanded infrastructure, farmer capacity-building, consumer behavior change, and improved resource management." Innovations in technology like the ones highlighted in this article will play a key role in this transformation.

DISCLOSURE STATEMENT

R.B. is a shareholder of DuPont, Caribou Biosciences, Intellia Therapeutics, Locus Biosciences, Inari Ag, Invaio, TreeCo, Ancilia Therapeutics, and CRISPR Biotechnologies. The authors are not aware of any other affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This material was partly based on work supported by grants from the National Institute of Food and Agriculture, USDA, Massachusetts Agricultural Experiment Station (MAS00491) and USDA, AFRI (2016-08782).

LITERATURE CITED

Adisa IO, Pullagurala VLR, Peralta-Videa JR, Dimkpa CO, Elmer WH, et al. 2019. Recent advances in nano-enabled fertilizers and pesticides: a critical review of mechanisms of action. *Environ. Sci.-Nano* 6:2002–30

Akhtar Y, Isman MB. 2018. Insects as an alternative protein source. In *Proteins in Food Processing*, ed. RY Yada, pp. 263–88. Cambridge, UK: Woodhead Publ. 2nd ed.

Akyazi T, Goti A, Oyarbide A, Alberdi E, Bayon F. 2020. A guide for the food industry to meet the future skills requirements emerging with industry 4.0. *Foods* 9(4):492

Alexander P, Brown C, Arneth A, Dias C, Finnigan J, et al. 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Glob. Food Secur. Agric. Policy Econ. Environ.* 15:22–32

Altpeter F, Springer NM, Bartley LE, Blechl AE, Brutnell TP, et al. 2016. Advancing crop transformation in the era of genome editing. *Plant Cell* 28:1510–20

Ashwar BA, Gani A, Shah A, Wani IA, Masoodi FA. 2016. Preparation, health benefits and applications of resistant starch: a review. *Starch-Starke* 68:287–301

Azcarate-Peril MA, Ritter AJ, Savaiano D, Monteagudo-Mera A, Anderson C, et al. 2017. Impact of short-chain galactooligosaccharides on the gut microbiome of lactose-intolerant individuals. *PNAS* 114(3):E367–75

Aziz M, Karboune S. 2018. Natural antimicrobial/antioxidant agents in meat and poultry products as well as fruits and vegetables: a review. *Crit. Rev. Food Sci. Nutr.* 58:486–511

Bahrami A, Moaddabdoost Baboli Z, Schimmel K, Jafari SM, Williams L. 2020. Efficiency of novel processing technologies for the control of *Listeria monocytogenes* in food products. *Trends Food Sci. Technol.* 96:61–78

Bevilacqua A, Petruzzi L, Perricone M, Speranza B, Campaniello D, et al. 2018. Nonthermal technologies for fruit and vegetable juices and beverages: overview and advances. *Compr. Rev. Food Sci. Food Saf.* 17:2–62

Bhat ZF, Morton JD, Mason SL, Bekhit AEA, Bhat HF. 2019. Technological, regulatory, and ethical aspects of in vitro meat: a future slaughter-free harvest. *Compr. Rev. Food Sci. Food Saf.* 18:1192–208

Bleakley S, Hayes M. 2017. Algal proteins: extraction, application, and challenges concerning production. *Foods* 6(5):33

Bordoni L, Gabbianelli R. 2019. Primers on nutrigenetics and nutri(epi)genomics: origins and development of precision nutrition. *Biochimie* 160:156–71

Braconi D, Bernardini G, Millucci L, Santucci A. 2018. Foodomics for human health: current status and perspectives. *Expert Rev. Proteom.* 15:153–64

Bumbudsanpharoke N, Choi J, Ko S. 2015. Applications of nanomaterials in food packaging. *J. Nanosci. Nanotechnol.* 15:6357–72

Cao Y, Shen J, Ran ZH. 2014. Association between *Faecalibacterium prausnitzii* reduction and inflammatory bowel disease: a meta-analysis and systematic review of the literature. *Gastroenterol. Res. Pract.* 2014:872725

Capuano E. 2017. The behavior of dietary fiber in the gastrointestinal tract determines its physiological effect. *Crit. Rev. Food Sci. Nutr.* 57:3543–64

Chen SE, Brahma S, Mackay J, Cao CY, Aliakbarian B. 2020. The role of smart packaging system in food supply chain. *J. Food Sci.* 85:517–25

Chung C, Smith G, Degner B, McClements DJ. 2016. Reduced fat food emulsions: physicochemical, sensory, and biological aspects. *Crit. Rev. Food Sci. Nutr.* 56:650–85

Claver H. 2019. Robotics to drive precision harvesting market. *Future Farming*. **https://www.futurefarming.com/Machinery/Articles/2019/10/Robotics-to-drive-precision-harvesting-market-479878E/**

Darvishi F, Ariana M, Marella ER, Borodina I. 2018. Advances in synthetic biology of oleaginous yeast *Yarrowia lipolytica* for producing non-native chemicals. *Appl. Microbiol. Biotechnol.* 102:5925–38

Davidson PM, Taylor TM, David JRD. 2020. *Antimicrobials in Food*. Boca Raton, FL: CRC Press

de Toro-Martin J, Arsenault BJ, Despres JP, Vohl MC. 2017. Precision nutrition: a review of personalized nutritional approaches for the prevention and management of metabolic syndrome. *Nutrients* 9:28

Delaney B, Goodman RE, Ladics GS. 2018. Food and feed safety of genetically engineered food crops. *Toxicol. Sci.* 162:361–71

Depommier C, Everard A, Druart C, Plovier H, Van Hul M, et al. 2019. Supplementation with *Akkermansia muciniphila* in overweight and obese human volunteers: a proof-of-concept exploratory study. *Nat. Med.* 25:1096–103

Deutsche Welle. 2020. Coronavirus: German slaughterhouse outbreak crosses 1,000. *Deutsche Welle*. **https://www.dw.com/en/coronavirus-german-slaughterhouse-outbreak-crosses-1000/a-53883372**

Dong HL, Ling Z, Zhang X, Zhang XM, Ramaswamy S, Xu F. 2020. Smart colorimetric sensing films with high mechanical strength and hydrophobic properties for visual monitoring of shrimp and pork freshness. *Sens. Actuators B* 309:127752

Donsi F, Ferrari G. 2016. Essential oil nanoemulsions as antimicrobial agents in food. *J. Biotechnol.* 233:106–20

Doudna JA, Sternberg SH. 2017. *A Crack in Creation: Gene Editing and the Unthinkable Power to Control Evolution*. Boston, MA: Houghton Mifflin Harcourt

Economist. 2020a. America's Covid-19 experience is tragic but not that exceptional. *The Economist*, May 28. **https://www.economist.com/briefing/2020/05/28/americas-covid-19-experience-is-tragic-but-not-that-exceptional**

Economist. 2020b. The world's food system has so far weathered the challenge of Covid-19. *The Economist*, May 9. **https://www.economist.com/briefing/2020/05/09/the-worlds-food-system-has-so-far-weathered-the-challenge-of-covid-19**

Economist. 2020c. How to feed the planet: the global food supply chain is passing a severe test. May 9. **https://www.economist.com/leaders/2020/05/09/the-global-food-supply-chain-is-passing-a-severe-test**

Eetemadi A, Rai N, Pereira BMP, Kim M, Schmitz H, Tagkopoulos I. 2020. The computational diet: a review of computational methods across diet, microbiome, and health. *Front. Microbiol.* 11:393

Es I, Gavahian M, Marti-Quijal FJ, Lorenzo JM, Khaneghah AM, et al. 2019. The application of the CRISPR-Cas9 genome editing machinery in food and agricultural science: current status, future perspectives, and associated challenges. *Biotechnol. Adv.* 37:410–21

Fasolin LH, Pereira RN, Pinheiro AC, Martins JT, Andrade CCP, et al. 2019. Emergent food proteins: towards sustainability, health and innovation. *Food Res. Int.* 125:108586

Field D, Cotter PD, Ross RP, Hill C. 2015. Bioengineering of the model lantibiotic nisin. *Bioengineered* 6(4):187–92

Finnigan TJA. 2011. Mycoprotein: origins, production and properties. In *Handbook of Food Proteins*, ed. GO Phillips, PA Williams, pp. 335–52. Cambridge, UK: Woodhead Publ.

Foley MH, O'Flaherty S, Barrangou R, Theriot CM. 2019. Bile salt hydrolases: gatekeepers of bile acid metabolism and host-microbiome crosstalk in the gastrointestinal tract. *PLOS Pathog.* 15:e1007581

Galanakis CM. 2020. The food systems in the era of the coronavirus (COVID-19) pandemic crisis. *Foods* 9:10

Gao BY, Holroyd SE, Moore JC, Laurvick K, Gendel SM, Xie ZH. 2019. Opportunities and challenges using non-targeted methods for food fraud detection. *J. Agric. Food Chem.* 67:8425–30

Gao BY, Qin F, Ding TT, Chen YN, Lu WY, Yu LL. 2014. Differentiating organically and conventionally grown oregano using ultraperformance liquid chromatography mass spectrometry (UPLC-MS), headspace gas chromatography with flame ionization detection (Headspace-GC-FID), and flow injection mass spectrum (FIMS) fingerprints combined with multivariate data analysis. *J. Agric. Food Chem.* 62:8075–84

Garcia P, Rodriguez L, Rodriguez A, Martinez B. 2010. Food biopreservation: promising strategies using bacteriocins, bacteriophages and endolysins. *Trends Food Sci. Technol.* 21:373–82

Gibney MJ, Forde CG, Mullally D, Gibney ER. 2017. Ultra-processed foods in human health: a critical appraisal. *Am. J. Clin. Nutr.* 106:717–24

Gibson E. 2019. The crucial ingredient our diet lacks. *BBC*. **https://www.bbc.com/future/bespoke/follow-the-food/the-crucial-ingredient-our-diet-lacks/**

Gidley MJ. 2013. Hydrocolloids in the digestive tract and related health implications. *Curr. Opin. Colloid Interface Sci.* 18:371–78

Gidley MJ, Yakubov GE. 2019. Functional categorisation of dietary fibre in foods: beyond "soluble" versus "insoluble." *Trends Food Sci. Technol.* 86:563–68

Gonzalez-Pena D, Brennan L. 2019. Recent advances in the application of metabolomics for nutrition and health. *Annu. Rev. Food Sci. Technol.* 10:479–519

Grundy MML, Edwards CH, Mackie AR, Gidley MJ, Butterworth PJ, Ellis PR. 2016. Re-evaluation of the mechanisms of dietary fibre and implications for macronutrient bioaccessibility, digestion and postprandial metabolism. *Br. J. Nutr.* 116:816–33

Gupta CG. 2016. *Nutraceuticals: Efficacy, Safety and Toxicity*. London: Academic

Hall KD, Ayuketah A, Brychta R, Cai HY, Cassimatis T, et al. 2019. Ultra-processed diets cause excess calorie intake and weight gain: an inpatient randomized controlled trial of ad libitum food intake. *Cell Metab.* 30:67–77.e3

Halonen N, Palvolgyi PS, Bassani A, Fiorentini C, Nair R, et al. 2020. Bio-based smart materials for food packaging and sensors: a review. *Front. Mater.* 7:82

Hensel K, Kuhn ME. 2020. Addressing a viral threat. *Food Technology Magazine*. **https://www.ift.org/news-and-publications/food-technology-magazine/issues/2020/may/features/addressing-a-viral-threat**

Holland C, Ryden P, Edwards CH, Grundy MML. 2020. Plant cell walls: impact on nutrient bioaccessibility and digestibility. *Foods* 9(2):201

Hruby A, Hu FB. 2015. The epidemiology of obesity: a big picture. *Pharmacoeconomics* 33:673–89

Ismail I, Hwang YH, Joo ST. 2020. Meat analog as future food: a review. *J. Anim. Sci. Technol.* 62:111–20

Jaenke R, Barzi F, McMahon E, Webster J, Brimblecombe J. 2017. Consumer acceptance of reformulated food products: a systematic review and meta-analysis of salt-reduced foods. *Crit. Rev. Food Sci. Nutr.* 57:3357–72

Jain A, Ranjan S, Dasgupta N, Ramalingam C. 2018. Nanomaterials in food and agriculture: an overview on their safety concerns and regulatory issues. *Crit. Rev. Food Sci. Nutr.* 58:297–317

Jambrak AR, Vukusic T, Donsi F, Paniwnyk L, Djekic I. 2018. Three pillars of novel nonthermal food technologies: food safety, quality, and environment. *J. Food Qual.* 2018:8619707

Joyce P, Whitby CP, Prestidge CA. 2016. Nanostructuring biomaterials with specific activities towards digestive enzymes for controlled gastrointestinal absorption of lipophilic bioactive molecules. *Adv. Colloid Interface Sci.* 237:52–75

Kabir E, Kaur R, Lee J, Kim KH, Kwon EE. 2020. Prospects of biopolymer technology as an alternative option for non-degradable plastics and sustainable management of plastic wastes. *J. Clean. Prod.* 258:120536

Kamle M, Mahato DK, Devi S, Soni R, Tripathi V, et al. 2020. Nanotechnological interventions for plant health improvement and sustainable agriculture. *3 Biotech* 10:168

Kamthan A, Chaudhuri A, Kamthan M, Datta A. 2016. Genetically modified (GM) crops: milestones and new advances in crop improvement. *Theor. Appl. Genet.* 129:1639–55

Kaphle A, Navya PN, Umapathi A, Daima HK. 2018. Nanomaterials for agriculture, food and environment: applications, toxicity and regulation. *Environ. Chem. Lett.* 16:43–58

Katouzian I, Jafari SM. 2016. Nano-encapsulation as a promising approach for targeted delivery and controlled release of vitamins. *Trends Food Sci. Technol.* 53:34–48

Kawamura AG. 2020. *Perspectives on COVID-19 and the Food and Agricultural System*. Presented at COVID-19 and the Food and Agricultural System, June 19. **https://www.nationalacademies.org/event/06-19-2020/covid-19-and-the-food-and-agricultural-system**

Khot LR, Sankaran S, Maja JM, Ehsani R, Schuster EW. 2012. Applications of nanomaterials in agricultural production and crop protection: a review. *Crop Prot*. 35:64–70

Kroger M, Meister K, Kava R. 2006. Low-calorie sweeteners and other sugar substitutes: a review of the safety issues. *Compr. Rev. Food Sci. Food Saf.* 5:35–47

Lange L, Meyer AS. 2019. Potentials and possible safety issues of using biorefinery products in food value chains. *Trends Food Sci. Technol.* 84:7–11

Liang D, Leung RK-K, Guan W, Au WW. 2018. Involvement of gut microbiome in human health and disease: brief overview, knowledge gaps and research opportunities. *Gut Pathog*. 10:3

Lu WY, Jiang QQ, Shi HM, Niu YG, Gao BY, Yu LL. 2014. Partial least-squares-discriminant analysis differentiating Chinese wolfberries by UPLC-MS and flow injection mass spectrometric (FIMS) fingerprints. *J. Agric. Food Chem.* 62:9073–80

Lu WY, Lv XX, Gao BY, Shi HM, Yu LL. 2015. Differentiating milk and non-milk proteins by UPLC amino acid fingerprints combined with chemometric data analysis techniques. *J. Agric. Food Chem.* 63:3996–4002

Maes WH, Steppe K. 2019. Perspectives for remote sensing with unmanned aerial vehicles in precision agriculture. *Trends Plant Sci*. 24:152–64

Maringer M, Wisse-Voorwinden N, van 't Veer P, Geelen A. 2019. Food identification by barcode scanning in the Netherlands: a quality assessment of labelled food product databases underlying popular nutrition applications. *Public Health Nutr*. 22:1215–22

MarketsandMarkets^{TM}. 2019. Precision harvesting market by product (combine, harvesting robots, forage harvesters), application (crop, horticulture, greenhouse), offering (hardware - sensors, gps, yield monitors, software, services), and geography: global forecast to 2023. *MarketsandMarkets*. **https://www.marketsandmarkets.com/Market-Reports/precision-harvesting-market-194202698.html**

Mattick CS. 2018. Cellular agriculture: the coming revolution in food production. *Bull. At. Sci.* 74:32–35

Mattick CS, Landis AE, Allenby BR, Genovese NJ. 2015. Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. *Environ. Sci. Technol.* 49:11941–49

McClements DJ. 2015. Nanoscale nutrient delivery systems for food applications: improving bioactive dispersibility, stability, and bioavailability. *J. Food Sci.* 80:N1602–11

McClements DJ. 2019. *Future Foods*: *How Modern Science is Transforming the Way We Eat*. New York: Springer Sci.

McClements DJ, Decker EA, Park Y, Weiss J. 2009. Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. *Crit. Rev. Food Sci. Nutr.* 49:577–606

McClements DJ, Newman E, McClements IF. 2019. Plant-based milks: a review of the science underpinning their design, fabrication, and performance. *Compr. Rev. Food Sci. Food Saf.* 18:2047–67

McDougall GJ, Stewart D. 2005. The inhibitory effects of berry polyphenols on digestive enzymes. *Biofactors* 23:189–95

McHugh AJ, Feehily C, Fenelon MA, Gleeson D, Hill C, Cotter PD. 2020. Tracking the dairy microbiota from farm bulk tank to skimmed milk powder. *mSystems* 5:e00226-20

Morales-de la Pena M, Welti-Chanes J, Martin-Belloso O. 2019. Novel technologies to improve food safety and quality. *Curr. Opin. Food Sci.* 30:1–7

Mozaffarian D. 2016. Dietary and policy priorities for cardiovascular disease, diabetes, and obesity: a comprehensive review. *Circulation* 133:187–225

Murray JD, Maga EA. 2016. Genetically engineered livestock for agriculture: a generation after the first transgenic animal research conference. *Transgenic Res*. 25:321–27

Nieman DC. 2020. Coronavirus disease-2019: a tocsin to our aging, unfit, corpulent, and immunodeficient society. *J. Sport Health Sci.* 9(4):293–301

O'Sullivan CA, Bonnett GD, McIntyre CL, Hochman Z, Wasson AP. 2019. Strategies to improve the productivity, product diversity and profitability of urban agriculture. *Agric. Syst.* 174:133–44

Ozdemir V, Kolker E. 2016. Precision nutrition 4.0: a Big Data and ethics foresight analysis—convergence of agrigenomics, nutrigenomics, nutriproteomics, and nutrimetabolomics. *Omics J. Integr. Biol.* 20:69–75

Pal A, Kant K. 2020. Smart sensing, communication, and control in perishable food supply chain. *ACM Trans. Sens. Netw.* 16:12

Park W. 2020. The farms growing beneath our cities. *BBC*. **https://www.bbc.com/future/bespoke/follow-the-food/the-massive-farms-emerging-beneath-our-cities.html**

Poore J, Nemecek T. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360:987–92

Quinto EJ, Caro I, Villalobos-Delgado LH, Mateo J, De-Mateo-Silleras B, Redondo-Del-Rio MP. 2019. Food safety through natural antimicrobials. *Antibiotics* 8:208

Randhawa G, Singh M, Sood P. 2016. DNA-based methods for detection of genetically modified events in food and supply chain. *Curr. Sci.* 110:1000–9

Rao JJ, Chen BC, McClements DJ. 2019. Improving the efficacy of essential oils as antimicrobials in foods: mechanisms of action. *Annu. Rev. Food Sci. Technol.* 10:365–87

Reuben A. 2020. Coronavirus: Why have there been so many outbreaks in meat processing plants? *BBC*. **https://www.bbc.com/news/53137613**

Ritala A, Hakkinen ST, Toivari M, Wiebe MG. 2017. Single cell protein-state-of-the-art, industrial landscape and patents 2001–2016. *Front. Microbiol.* 8:2009

Saladino D. 2020. Covid-19: the food waste dimension. *The Food Programme*. **https://www.bbc.co.uk/sounds/play/m000hmnd**

Saleem H, Trabzon L, Kilic A, Zaidi SJ. 2020. Recent advances in nanofibrous membranes: production and applications in water treatment and desalination. *Desalination* 478:114178

Salvia-Trujillo L, Soliva-Fortuny R, Rojas-Grau MA, McClements DJ, Martin-Belloso O. 2017. Edible nanoemulsions as carriers of active ingredients: a review. *Annu. Rev. Food Sci. Technol.* 8:439–66

Scazzina F, Siebenhandl-Ehn S, Pellegrini N. 2013. The effect of dietary fibre on reducing the glycaemic index of bread. *Br. J. Nutr.* 109:1163–74

Selle K, Fletcher JR, Tuson H, Schmitt DS, McMillan L, et al. 2020. In vivo targeting of *Clostridioides difficile* using phage-delivered CRISPR-Cas3 antimicrobials. *mBio* 11:e00019-20

Shafi U, Mumtaz R, Garcia-Nieto J, Hassan SA, Zaidi SAR, Iqbal N. 2019. Precision agriculture techniques and practices: from considerations to applications. *Sensors* 19(17):3796

Shamshiri RR, Kalantari F, Ting KC, Thorp KR, Hameed IA, et al. 2018. Advances in greenhouse automation and controlled environment agriculture: a transition to plant factories and urban agriculture. *Int. J. Agric. Biol. Eng.* 11:1–22

Shao Y, Forster SC, Tsaliki E, Vervier K, Strang A, et al. 2019. Stunted microbiota and opportunistic pathogen colonization in caesarean-section birth. *Nature* 574:117–21

Sharma R, Jafari SM, Sharma S. 2020. Antimicrobial bio-nanocomposites and their potential applications in food packaging. *Food Control* 112:107086

Shveda K. 2020. How coronavirus is changing grocery shopping. *BBC*. **https://www.bbc.com/future/bespoke/follow-the-food/how-covid-19-is-changing-food-shopping.html**

Singh VP. 2018. Recent approaches in food bio-preservation: a review. *Open Vet. J.* 8:104–11

Sirohi R, Pandey JP, Gaur VK, Gnansounou E, Sindhu R. 2020. Critical overview of biomass feedstocks as sustainable substrates for the production of polyhydroxybutyrate (PHB). *Bioresour. Technol.* 311:123536

Sloan AE. 2020. The top 10 functional food trends. *Food Technology Magazine*. **https://www.ift.org/news-and-publications/food-technology-magazine/issues/2020/april/features/the-top-10-functional-food-trends**

Sozer N, Kokini JL. 2009. Nanotechnology and its applications in the food sector. *Trends Biotechnol.* 27:82–89

Specht L. 2018. Is the future of meat animal-free? *Food Technol.* 72:17–21

Standage T. 2009. *An Edible History of Humanity*. New York: Walker Publ.

Stewart CJ, Ajami NJ, O'Brien JL, Hutchinson DS, Smith DP, et al. 2018. Temporal development of the gut microbiome in early childhood from the TEDDY study. *Nature* 562:583–88

Tay MZ, Poh CM, Renia L, MacAry PA, Ng LFP. 2020. The trinity of COVID-19: immunity, inflammation and intervention. *Nat. Rev. Immunol.* 20:363–74

Thakur D, Kumar Y, Kumar A, Singh PK. 2019. Applicability of wireless sensor networks in precision agriculture: a review. *Wireless Pers. Commun.* 107:471–512

U.N. 2019. *World population prospects 2019: highlights*. Rep., Dep. Econ. Soc. Aff., New York. **https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf**

Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, et al. 2020. Nanotechnology in agriculture: current status, challenges and future opportunities. *Sci. Total Environ.* 721:137778

van Huis A, Oonincx D. 2017. The environmental sustainability of insects as food and feed. A review. *Agron. Sustain. Dev.* 37:43

Venkatalakshmi P, Vadivel V, Brindha P. 2016. Role of phytochemicals as immunomodulatory agents: a review. *Int. J. Green Pharm.* 10(1):1–18

Vilsack T. 2020. *Perspectives on COVID-19 and the food and agricultural system*. Presented at COVID-19 and the Food and Agricultural System, June 19. **https://www.nationalacademies.org/event/06-19-2020/covid-19-and-the-food-and-agricultural-system**

Waschulin V, Specht L. 2018. *Cellular agriculture: an extension of common production methods for food*. Rep., Good Food Inst., Washington, DC. **https://www.gfi.org/images/uploads/2018/03/Cellular-Agriculture-for-Animal-Protein.pdf**

WEF (World Econ. Forum). 2019. *Innovation with a purpose: the role of technology innovation in accelerating food systems transformation*. Rep., World Econ. Forum, Geneva, Switz. **http://www3.weforum.org/docs/WEF_Innovation_with_a_Purpose_VF-reduced.pdf**

Wiebe MG. 2002. Myco-protein from *Fusarium venenatum*: a well-established product for human consumption. *Appl. Microbiol. Biotechnol.* 58:421–27

Wilde M. 2020. Autonomous planting revs up: farmers hire robotic firm to plant soybeans. *Progressive Farmer*. **https://www.dtnpf.com/agriculture/web/ag/crops/article/2020/05/06/farmers-hire-robotic-firm-plant**

Willett W, Rockstrom J, Loken B, Springmann M, Lang T, et al. 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet* 393:447–92

Williams BA, Mikkelsen D, Flanagan BM, Gidley MJ. 2019. "Dietary fibre": moving beyond the "soluble/insoluble" classification for monogastric nutrition, with an emphasis on humans and pigs. *J. Anim. Sci. Biotechnol.* 10:45

Wink M. 2003. Evolution of secondary metabolites from an ecological and molecular phylogenetic perspective. *Phytochemistry* 64:3–19

Wunderlich S, Gatto KA. 2015. Consumer perception of genetically modified organisms and sources of information. *Adv. Nutr.* 6:842–51

Xiao JB, Ni XL, Kai GY, Chen XQ. 2013. A review on structure-activity relationship of dietary polyphenols inhibiting α-amylase. *Crit. Rev. Food Sci. Nutr.* 53:497–506

Yang MY, Cousineau A, Liu XB, Luo YG, Sun D, et al. 2020. Direct metatranscriptome RNA-seq and multiplex RT-PCR amplicon sequencing on nanopore MinION: promising strategies for multiplex identification of viable pathogens in food. *Front. Microbiol.* 11:514

Yuan JJ, Lu YL, Cao XH, Cui HT. 2020. Regulating wildlife conservation and food safety to prevent human exposure to novel virus. *Ecosyst. Health Sustain.* 6:1741325

Zafar S, Li YL, Li NN, Zhu KM, Tan XL. 2019. Recent advances in enhancement of oil content in oilseed crops. *J. Biotechnol.* 301:35–44

Zhang RJ, McClements DJ. 2016. Enhancing nutraceutical bioavailability by controlling the composition and structure of gastrointestinal contents: emulsion-based delivery and excipient systems. *Food Struct.* 10:21–36