Lloyd's Register Foundation

Foresight review of food safety

Feeding the world safely and sustainably

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About Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by Lloyd's Register Foundation. It is hoped that these reports will provide insights for research, policy and business communities and inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Executive summary

An estimated 600 million people, almost 1 in 10 people in the world, fall ill as a result of eating contaminated food and 420,000 die every year. In 2004, 160 countries voted at the United Nations to make food – safe food – a human right rather than a commodity, but risks to safety continue with many challenges putting strains on supply chains. The world is in the midst of a nutritional transition, facing over-nutrition in some regions and under-nutrition in others. With the global population expected to exceed nine billion by 2050, pressures have been placed on existing food systems and this has implications for food safety. Foodborne illnesses, from E. coli to listeria, threaten lives and everyone – consumers, companies and governments – has an important role to play in improving the status quo.

The cost of unsafe food is high. The United States Department of Agriculture (USDA) estimates that foodborne illnesses cost the United States (US) at least $15.6 billion annually in lost productivity and medical care. There are environmental and social costs to food production too. The global food production system is one of the biggest contributors to greenhouse gas emissions. People today must consider alternative energy and food sources to limit the depletion of natural resources tomorrow.

We know we must take action, but many challenges stand in our way. Complex supply chains open up risks to food fraud, and a lack of traceability frustrates consumers' abilities to understand the authenticity of what they are buying. Keeping food safe can harm the environment: plastic packaging is now an urgent global concern and food cold chains, while an important part of food safety, have a negative impact on energy consumption and sustainability. At a time when food safety needs a funding boost, global research and innovation investment in food is low relative to other industries.

The fast-growing demand for food puts an enormous strain on the food production system and natural resources. If the current global population were to consume the same amount per head of meat as Europe, five planets covered with grazing land – ocean included – would be needed. The future food safety system must be sustainable and take into account this growing demand. At the same time, it must also take into account food loss and waste and address the lack of efficiency. Underlying these challenges is a need for education and training about food safety. From consumers, to companies, to governments, people need more evidence-based information in order to make informed decisions about the food they eat.

But solutions are at hand. Technology can play an important part in addressing these challenges. In the life sciences, new ways of producing proteins - lab meat, insects, seafood - can help improve not only traceability but also sustainability; aquaculture or aquafarming is the fastest-growing animal food-producing sector in the world. Urban farming and 3D-printed food help in the production of local, traceable food. New techniques in DNA verification and next-generation sequencing are opening up possibilities for genetically modifying food for greater safety. The microbiome – a community of beneficial microorganisms such as bacteria, fungi and viruses that inhabit environments including the human body – could one day become our frontline in food safety. And stable isotope technology gives us a way to 'fingerprint' food and help prevent fraud.

Data science and life science are about to converge to shape a new model for food safety. Big data and predictive analytics can aggregate and analyse immense volumes of information through complex algorithms to anticipate risks or critical events in the food supply chain before they happen. The internet of things will help improve the efficiency and productivity of factories and improve traceability. Agricultural drones and satellites can help identify and warn against crop pests. Blockchain – a technology that combines the openness of the internet with the security of cryptography to give a faster, safer way to verify information and establish trust – promises to revolutionise traceability in the food supply chain. It can help to tackle food fraud and deliver the information that consumers need about the food they consume.

Social evolutions are also changing the face of food safety. A new generation of consumers is driving a food revolution. These trend setters have a new set of values: they want food that is healthy but, importantly, they also want food that is sustainable and free from animal abuse, genetically modified organisms (GMOs) and modern slavery. Following the Wikipedia and OpenStreetMap (the free wiki world map) examples, open food databases driven by citizens are gaining increasing momentum and are a big issue for food brands. Vegan, vegetarian and organic consumption are growing fast and now represent more of an ideology or lifestyle than just a diet.

To embrace the opportunities that lie ahead, it is recommended that Lloyd's Register Foundation focuses investment in three core areas. First, education and training in developed and developing countries: an interconnected approach that brings academia, citizens, governments, industry and non-governmental organisations together to act on solutions. Second, traceability in the food supply chain and development of a broad range of technologies to connect the steps and make food more traceable and, therefore, safer for consumers. Third, delivering an ocean of food: investing in aquaculture and seafood production for greater food safety and sustainability, focusing on improving current practices, and expanding and upscaling for the future.

Foreword

With an estimated 600 million cases of foodborne illnesses annually, unsafe food is a major concern to human health and economies globally. In addition, too often food scandals due to fraud or inappropriate processes are making headlines. The cost for these food safety issues is huge notably in low and middle income countries (US$100 billion according to the World Bank). Our global food system was built in the second half of the 20th century and now needs re-engineering to keep the pace with social and technological changes.

Food safety causes public anxiety and is subject to escalating media attention. Still, we should not think negatively about the future of our food system; the world is waking up to the challenges we face. Indeed, the food system has managed to decrease the proportion of people going to bed hungry every day from 40% to 9% while, at the same time, global population has grown from 5 to 7.5 billion and expectations around food safety have skyrocketed. The food industry can be proud of what it has achieved but, still, it cannot rest. It must embrace new and sustainable ways of addressing the global imbalance in food availability and food safety.

The goal of this foresight review is to gather experts' insights and provide information for a wider debate in society, including among practitioners, about food safety challenges, evidence-based approaches to further investigate food safety and action to limit this growing global public health risk. This work builds on the strong credentials developed by Lloyd's Register Group in food assurance and considers how the growing world population could be fed with high quality, safe and affordable food, while taking into account the sustainability of our planet.

Investments are needed in research, innovation and education to speed up this change. The entire food industry must harness the incredibly rich food expertise from around the world and make the most of evolving and new disruptive technologies to create a transparent, traceable and safe food system. The ingredients are there for a food safety revolution.

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Background

This report is the first by Lloyd's Register Foundation as part of its food safety challenge. It looks at the current challenges in the food supply chain and how new technologies and trends could help to evolve a new food safety system.

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Lloyd's Register Foundation is a charity and owner of Lloyd's Register Group Limited (LR). LR is a 259-year-old organisation providing independent assurance and expert advice to companies operating high-risk, capitally intensive assets primarily in the energy, maritime and transportation sectors. It also serves a wide range of sectors with distributed assets and complex supply chains such as the food, healthcare, automotive and manufacturing sectors.

Building on the findings of this foresight review, the Foundation will look to identify aspects of food safety that might provide opportunities or threats to safety in line with its charitable objectives. It will also look at where the Foundation may focus its research and other grant giving to make a distinctive positive impact.

The Foundation is a charity with a global role. Reflecting this, it assembled international and cross-sectoral expert panels which met from October 2018 to January 2019 in a series of advisory workshops. This report contains the output and findings from those workshops.

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Food safety matters

"If food isn't safe, it isn't food. We cannot hope to end hunger and create a #ZeroHunger world without this basic building block." – UN Food and Agriculture Organization (FAO)[1]

In 2004, 160 countries voted at the United Nations (UN) to make food a human right rather than a commodity. It was agreed that everyone on the planet should have access to sufficient food, both quantitatively and qualitatively, in a culturally acceptable way.

Unsafe food, containing harmful bacteria, viruses, parasites, chemical substances or physical contaminants, causes more than 200 diseases ranging from diarrhoea to cancers. An estimated 600 million people – almost one in 10 people in the world – fall ill as a result of eating contaminated food and 420,000 die every year. Diarrhoeal diseases are the most common foodborne acute illnesses, causing 550 million people to fall ill with 230,000 deaths every year. It is estimated that due to 31 foodborne hazards, foodborne diseases resulted in the loss of 33 million disability-adjusted life years (DALYs) in 2010[2]. Over time, food tainted by pesticides, or containing sub-therapeutic doses of antibiotics that accumulate in the human body, can lead to chronic diseases. Seventy percent of global cases of foodborne disease are concentrated in sub-Saharan Africa and South/Southeast Asia, and 40% of the burden falls on children under five years of age resulting in 125,000 deaths per year.

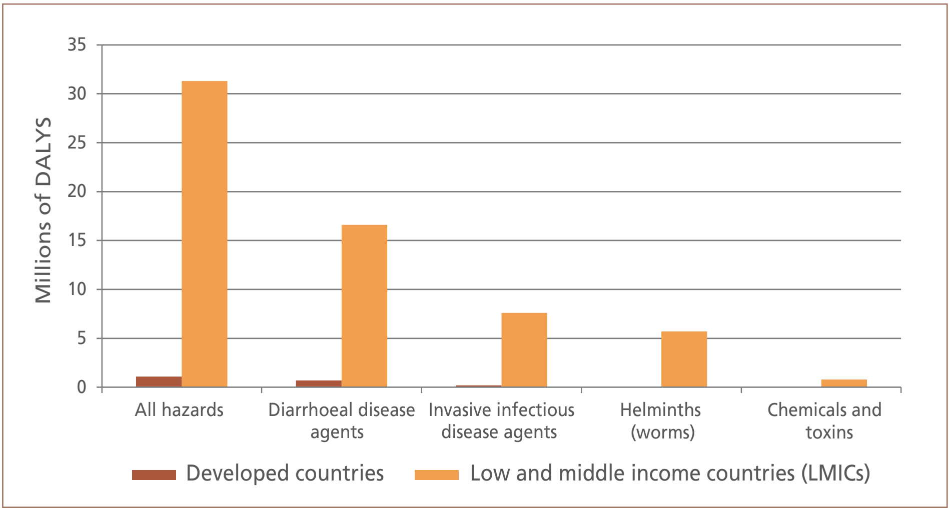


Figure 1: Global burden of foodborne disease (DALYs)[3].

Biological hazards (viruses, bacteria, fungi and parasites) cause 97% of the total burden in low and middle income countries (LMICs). Fruits, vegetables and animal-source foods are among the most nutrient-rich, but mounting evidence suggests they are also often the most contaminated foods, especially when sourced in informal markets[4]. The UN World Health Organization (WHO) reported that the global burden of foodborne disease is comparable to those of three major infectious diseases: HIV/AIDS, malaria and tuberculosis[5]. Despite this, financial investment in food safety remains comparatively low.

Furthermore, the world is currently in the midst of a nutritional transition with people's diets, especially in LMICs, becoming more dominated by livestock, sugar and saturated fat, all of which are linked to rising obesity and diabetes[6]. Given the emergence of both unsustainable and unhealthy diets, agencies like the United States Department of Agriculture (USDA) offer nutritional guidelines on balanced diets. However, if everyone were to follow the USDA dietary guidelines for all food groups (oils, grains, meat and pulses, fruit and vegetables, and dairy), an enormous amount of additional fertile land would be needed in order to produce enough food to feed the world.

With global population expected to exceed nine billion by 2050, the need for land will continue to rise[7]. In addition to dietary health concerns, challenges include water conservation, production of greenhouse gas (GHG) emissions, loss of biodiversity resulting from feeding a growing population and access to natural resources such as land. Strategies for conserving water will include changing diets, developing drought-resistant crops and livestock, and even managing water through policy and trade initiatives.

Food safety, nutrition, food security and sustainability are closely linked. Unsafe food makes the vicious cycle of disease and malnutrition worse, particularly affecting infants, young children, the elderly, the immune-compromised and the sick. Foodborne diseases obstruct socioeconomic development by straining health care systems and harming national economies, tourism and trade.

As rising incomes swell the demand for fresh foods, and urbanisation increases the volume of food being transported between food producers and consumers, the burden of foodborne disease is expected to increase in emerging economies. At the same time, it is likely that nutritional value will decline. This trend is counter to that of infectious diseases, which generally decline as nations develop.

As growing urbanisation, changing purchasing power and new systems of marketing change food access and consumption patterns, consumers need to be better informed and empowered with the tools to make nutritious and safe food choices – even if it means returning to the more traditional way of eating seasonally-produced food.

From a cultural point of view, improving management and hygiene practices in the food and agricultural sectors can help to reduce the outbreak and spread of foodborne diseases. Reducing the use of antibiotics in livestock and seafood could also decrease the risk of antimicrobial resistance along the food chain and in the environment.

Major foodborne illnesses and causes

Foodborne illnesses are usually infectious or toxic in nature and caused by bacteria, viruses, parasites or chemical substances entering the body through contaminated food or water. Foodborne pathogens (organisms that cause diseases) can cause severe diarrhoea or debilitating infections including meningitis. Chemical contamination can lead to acute poisoning or long-term diseases such as cancer. Foodborne diseases may lead to long-lasting disability and death. Recent reports of the widespread detection of microplastics in water, food and human faeces have raised the spectre of another contaminant of significant concern[8].

Food scandals: Peanut Corporation of America

The largest food scandal in history was the 2009 outbreak of salmonella in the US involving the Peanut Corporation of America (PCA). It followed a long history of food quality issues: individuals had concerns about sanitation at the company from the mid-1980s. During this 2009 incident, nine people died and at least 714 people (half of them children) fell ill, all from food poisoning after eating products containing contaminated peanuts. The event triggered the most extensive food recall in US history, involving 46 states, more than 360 companies and more than 3,900 different products manufactured using PCA ingredients. It also had immediate, major impacts on the product's market as well as on public perceptions of food safety and government regulation. In February 2009, PCA ceased all manufacturing and business operations and filed for Chapter 7 bankruptcy liquidation. A federal criminal investigation took place and at least a dozen civil lawsuits were filed. In September 2015, the general manager was sentenced to 28 years in prison for his role in the nationwide outbreak after being convicted of more than 70 criminal charges[9].

Major foodborne illnesses and causes

Salmonella, campylobacter, E. coli

- Among the most common foodborne pathogens with sometimes fatal outcomes
- From eggs, poultry and other products of animal origin and fresh produce

Listeria

- Can lead to miscarriage in pregnant women and death among the young and elderly
- From unpasteurised dairy products and ready-to-eat foods

Vibrio cholerae

- Can lead to abdominal pain, vomiting and diarrhoea that can lead to dehydration and death
- From rice, vegetables, millet gruel and various types of seafood

Antimicrobials

- Low doses of antibiotics can affect normal human gut flora and lead to chronic diseases and the emergence of resistant strains of pathogens (AMR)
- From overuse and misuse in veterinary and human medicine

Viruses

- Can lead to nausea, vomiting and diarrhoea; Hepatitis A can cause long-lasting liver disease
- From raw or undercooked seafood or contaminated raw produce

Parasites

- Can lead to mild discomfort but, in severe cases, death
- From food or direct contact with animals; parasites enter food chain via water or soil

Prions

- Specific forms of neurodegenerative disease such as BSE ('mad cow disease')
- From infectious agents composed of proteins in diseased cattle

Chemicals

- Can affect immune systems, normal development in children, or cause cancer
- From many sources including pesticides

Natural toxins

- Can result in various symptoms; various types of toxicity (genotoxic, carcinogenic, paralytic, diarrhoeic, endocrine disrupting etc)
- Naturally produced; sources include mycotoxins (produced by fungi), fycotoxins (also called marine toxins, found in shellfish), phytotoxins (produced by plants)

Heavy metals (such as lead, cadmium, mercury and arsenic)

- Can cause neurological and kidney damage
- From pollution of air, water and soil

Contaminants and endocrine disruptors

- Chemicals that pose risks during prenatal and early postnatal development
- From a wide range of substances, both natural and man-made such as pesticides

Soy as an example natural endocrine disruptor

Soy has a high nutritional value and has developed an arsenal to face its predators; among these weapons are estrogenic isoflavones (strong estrogenic endocrine disruptors), which are resistant to heat but soluble in water. Traditional soy recipes removed all anti-nutritional factors by prolonged cooking, simmering or soaking in hot water but these steps are now omitted to save energy and environmental costs. Consequently, the isoflavone exposure most probably rose dramatically in modern times and it can act synergistically together with other endocrine disruptors. A negative impact on human fertility is strongly considered while the positive effects of these compounds should be reserved to specific physiological status using food supplements or phyto-drug. New industrial processes to remove isoflavones from soy-based food products should be investigated[10].

The cost when food safety goes wrong

It is clear that unsafe food results in costs to consumers, businesses and society. Consumers who become ill bear medical costs, lost days of work and productivity, physical suffering and even mortality. Foodborne illness tends to be a greater burden on poor people and on women, children and the elderly.

Recently the World Bank estimated that foodborne illness costs LMICs at least $100 billion annually in lost productivity and medical costs. The USDA estimates that foodborne illnesses cost the US at least $15.6 billion annually in similar losses. However, these figures do not take into account specific losses to firms or industries from costs associated with limiting risk or lost market opportunities.

Firms bear the costs of food safety in many ways. They may adopt measures to improve food safety or avoid hazards and these can impose direct costs. Modern food safety management includes the cost of monitoring and training to ensure compliance with good practices. When food safety failures happen, such as product recalls, they impose direct losses on firms as well as potential liability costs from impacted customers. Food safety failures may reduce equity value for firms and may lead to bankruptcy. An entire industry can suffer loss of markets when food safety failures occur, so that even firms and brands with good food safety are penalised through the loss of reputation by association[11].

Many food safety controls and procedures have fixed, up-front costs. Thus, costs tend to fall more heavily on small firms and enterprises, as they experience higher costs of compliance per unit produced. In some cases, the loss of workforce in small and medium-sized food processing enterprises caused by modernisation and enforcement of international food safety standards can be as high as 75%. Compliance costs have been estimated between US$250,000 and US$1.6 million for a small to medium-sized enterprise.

In recent decades, trade in high value food products has quickly expanded, with many LMICs exporting fresh and perishable products to high income countries. These exports have been disrupted due to lack of compliance with food safety requirements imposed by importing countries or by multi-national firms. Concerns have been raised about the impact on trade and development, even though disruptions appear to be small relative to the total volume of trade. Similar issues are now apparent in the rapidly-developing markets of middle income countries, where urban consumers, concerned about potential hazards in locally sourced products, prefer to buy imported foods through expanding e-commerce channels. This may skew development of markets towards food imports and put domestic producers at a disadvantage.

By 2050, two out of three people will live in megacities (10 million residents or more), so adequate investment is needed to address challenges with food distribution, sanitation and hygiene, food waste and water scarcity. Ensuring food safety is a shared responsibility along the value chain is important; improvements will require public-private partnerships, education and investments in all stages of food production as well as actionable information for consumers about how to avoid risks. Investment in consumer food safety education and communication has the potential to reduce foodborne disease and return significant savings.

Food safety is a critical enabler for market access and productivity, which drives economic development and poverty alleviation, especially in rural areas. It will be a key driver in the development of food markets, growth of farm income, small firm revenue and health of growing urban populations.

Environmental and social implications of food safety

Perhaps our biggest responsibility is related to the environmental and social impacts caused by the food system that we favour. The current generation is the first one to truly recognise these issues and know that the global food production system is one of the biggest contributors of GHG emissions. This generation must consider alternative energy and food sources to limit the depletion of natural resources, land erosion, deforestation and massive pollution of the land and the oceans. It is now also clear that food systems have a degree of responsibility for an explosion of non-communicable diseases including obesity, diabetes and several forms of cancer.

In the wider social context of food safety, we must acknowledge that our food system is partly responsible for the rapid increase of modern slavery. There are 25 million people in a state of modern slavery today12, twice more than over the 300 years of human traffic

Modern slaves in the Southeast Asian seafood supply chain

Most of the Southeast Asian seafood industry relies on an international migrant workforce; people who are often poorly paid and work in highly authoritarian and coercive systems. It is difficult to accurately estimate the number of workers on fishing boats in this region, but it is likely to be well over 100,000.

The most common means of coercion has been economic (withholding wages), but a significant proportion (3% overall and 5% of workers from Myanmar) have reported violence and the threat of violence. There have even been reports of executions. This situation has been enabled, in part, because employers can easily evade regulation given the informal nature of recruitment, the distance boats travel and the limited time workers spend onshore.

Information about labour abuse in the seafood industry has emerged over the past five years from journalists and non-governmental organisations (NGOs). Specifically, journalists showed how offshore fishing boats that abused and held workers as captives sold trash fish to processors, which was subsequently used to feed farmed shrimp exported by major companies to international brands and retailers[13]. These companies had to publicly acknowledge weaknesses in ensuring their supply chains were absent of modern slavery. These events led to the Modern Slavery Act, which was signed into law in the UK in 2015.

between Africa and America. Modern slavery includes child labour, forced labour and human trafficking. Though most of the shocking scandals have emerged in the seafood industry in Southeast Asia, it is also known that coffee, tea, sugar and cocoa are the main commodities contributing to the rise of modern slavery in the world today.

It is also worth mentioning the high level of suicide among modern farmers, which is likely due to harsh working conditions with low return on labour but could also be linked to exposure to pesticides and antibiotics.

Climate change alters where and how often food safety hazards appear. A change in climate leads to changed patterns, for example, of food contamination from pathogens, toxins and heavy metals (for example cadmium and mercury). This needs to be considered when addressing future challenges.

Despite growing recognition of the fundamental role that food safety plays in achieving the UN Sustainable Development Goals (SDGs) and the main objectives of the UN Decade of Action on Nutrition, efforts to strengthen food safety systems remain fragmented. The gains, particularly in many LMICs, have been well below expectations and there is a need for global commitment and innovation.

As countries develop their economies and industries, the issue of feeding the population moves from food security to food safety as well as to land use, soil depletion and being able to maintain a supply of traditional foods and ingredients. Furthermore, as outlined above, consumption of microplastics is becoming an important issue that needs investigation.

At the same time, LMIC diets are shifting to mirror western diets, hand in hand with people's aspirations for progress. These diets, beside the high fat and sugar content, tend to lack diversity in the number of plants eaten, which leads to poor gut health, resulting in a rise in obesity and a decrease in nutrient absorption. Evidence is emerging that countries will change from under-nutrition to over-nutrition and obesity in a few years.

How is food safety being addressed today?

Food has never been as safe as it is today, but there is reason for concern as we feed a growing global population. Food safety is considered a non-competitive or pre-competitive topic for the food-producing industry in most countries. It has been enforced around the world by the collective effort of the food processing and retail industry through joint food safety initiatives and standards as well as governments through regulations, enforcement of standards and establishment of international guidelines.

Food testing has now reached a high level of sophistication and has been adopted into the mainstream – in developed economies at least. The recent consolidation of this international market around a few specialised commercial food laboratories has created an unprecedented level of investment in food testing research, which has now been boosted by recent DNA sequencing innovations, field test kits, and smartphone and handheld detection technologies.

Yet societal mega-trends create a situation that is challenging for everyone. These trends include population growth, urbanisation, global warming and environmental issues, the emergence of new pathogens, a higher level of food safety sensitivity from consumers and financially-motivated food fraud.

Governments and food safety

Food safety concerns governments in different ways, especially when we look at developed versus LMICs, for example, problems from over- and under-nutrition. All governments must support more education around food safety but with a different focus on the types of knowledge and information depending on the region.

Developed countries

Internationally, food safety standards align with the Codex Alimentarius, which is intended to, "… guide and promote the elaboration and establishment of definitions and requirements for foods to assist in their harmonisation and … to facilitate international trade"[8].

The Codex Alimentarius is a collection of internationally recognised standards, codes of practice, guidelines and other recommendations relating to foods, food production and food safety. The texts are developed and maintained by the Codex Alimentarius Commission, which was jointly established in 1962 by the FAO and WHO. The Commission's main goal is to protect the health of consumers. It is recognised by the World Trade Organization as an international reference point for the resolution of disputes concerning food safety and consumer protection.

As of 2012, there were 187 members of the Codex Alimentarius Commission: 186 member countries and one member organisation, the European Union (EU). There were 215 observers: 49 intergovernmental organisations, 150 non-governmental organisations and 16 UN organisations.

The Codex Alimentarius aims to help consumers trust the safety and quality of food products and to help importers trust that the food they ordered meets their specifications. Veterinary drugs, pesticides, food additives and contaminants are some of the issues discussed in Commission meetings. Codex Alimentarius standards are based on guidance provided by independent international risk assessment bodies or ad hoc consultations organised by the FAO and WHO. While these standards are essentially recommendations to be applied voluntarily by members, in many cases they serve as a basis for national legislation.

These national regulations are constantly evolving to ensure they meet current standards. The most recent significant development is the Food Safety Modernization Act (FSMA) enforced by the Food and Drug Administration in the US. It introduced the most substantial reform of food safety laws in more than 70 years and was signed into law by President Obama in 2011. It aims to ensure the US food supply is safe by shifting the focus from responding to contamination and 'end-product testing' to preventing contamination in the first place, moving primary responsibility to food producers and manufacturers.

While the FSMA is US legislation, its impacts reach beyond the US border to any food company looking to export its products to the US or supply US food companies. The new regulation requires any company exporting to the US to demonstrate training or expertise in preventive controls. This is a significant development given that more than 250,000 suppliers from approximately 150 countries export food products to the US.

In the EU, food safety is handled by the European Food Safety Authority (EFSA), a European agency funded by the EU that operates independently of the European legislative and executive institutions (the European Commission, Council and Parliament) and EU member states. EFSA was created in 2002, following a series of food crises in the late 1990s, to be a source of scientific advice and communication on risks associated with the food chain. The General Food Law created a European food safety system in which responsibility for risk assessment (science) and risk management (policy) are kept separate. EFSA is responsible for the former area and for communicating its scientific findings to the public. It produces scientific opinions and advice that form the basis for European policies and legislation on food and feed safety, nutrition, animal health and welfare, plant protection and plant health.

Low and middle income countries (LMICs)

Consuming unsafe foods poses a significant public health threat in LMICs. This is especially true in Africa. Infants, young children, pregnant women, the elderly and those with underlying illnesses are particularly vulnerable. Food and water containing harmful bacteria, viruses, parasites or chemical substances are responsible for more than 200 diseases in these regions while meats, seafood, cooked rice, cooked pasta, milk, cheese and eggs are common types of food that can quickly become unsafe. Furthermore, malnutrition can negatively impact the effectiveness of vaccination, meaning infectious diseases are impacted by lack of nutrition.

In most LMICs, the vast majority of livestock and seafood products are sold in 'wet' markets that sell perishable goods or informal markets (up to 80% in most sub-Saharan countries)[10]. These are markets that escape the usual health and safety regulations, are often untaxed or unlicensed and where traditional processing, products and affordable prices predominate. Informal markets generally sell food at lower prices than formal markets, while being closer and more accessible to consumers. These kinds of markets are growing quickly because of a rapid increase in population, especially in cities, towns and their surrounding areas, presenting a higher risk of pathogens or potential hazardous substances.

Assessing foodborne disease in LMICs is difficult because many infectious diseases never receive a definitive diagnosis. Even if a diagnosis is given, it may be difficult to know if the source of the pathogen was food, water, other people, animals or the environment. Moreover, there is a perception that foodborne disease is a minor inconvenience and largely unavoidable. Foodborne diseases in LMICs negatively impact economies, trade and market access, and have more complicated effects on nutrition and equity. This is particularly the case in Africa with its booming population but is also true in Asia due to urbanisation and poor management of the food supply chain. Foodborne illnesses pose serious problems for poor and vulnerable people, who cannot afford to fall ill because of the physical demands of their work.

Due to their costs and complexity risk-based food safety management and the use of system-wide audit controls have not yet been implemented in most of the food systems of LMICs. Consequently, there is a real need to adapt the risk-based model for emerging economies and, more importantly, build skills in the application of these models.

Most food safety issues in these countries are associated with improper post-processing handling of food, notably a lack of personal hygiene such as hand washing prior to preparing food. The lack of transparency and increased food fraud in low income countries also adversely affects good food safety practices.

Understanding values and cultures is essential to managing food safety in this part of the world and indigenous knowledge is important for a proper application of key concepts. A good, balanced diet is not defined the same everywhere and, while it can be difficult to change traditional practices that represent high risks, there are different cultural beliefs about hazards associated with food.

Gender and food safety

From a gender perspective, women are often excluded from decision-making in different segments of the food value chain. There has been little research into gender and food safety, but foodborne diseases can have important implications for women's resilience and vulnerability.

First, food safety has direct implications for women's health. Pregnant and lactating women are especially vulnerable because of their changing immune systems. Some pathogens cause foetal abnormalities, miscarriages and stillbirths and some chemical hazards can be transmitted to the new-born through breast milk. Second, cultural practices can affect the consumption of risky foods by men and women, for example, women consume more low-value offal and men more high-value muscle meat. Women are often excluded from more sophisticated parts of the food value chain (food processing, for example) where they could impact risk and safety. Last, women can act as 'risk managers' in relation to food consumption, preparation, processing and selling but are often disadvantaged because they have less access to education.

When it comes to LMICs, measures to limit risk need local training, skills development and to relate to the local culture. In the meantime, a thorough assessment is needed in terms of economic gains and potential losses in these environments.

Industry and food safety

The food industry has recently launched various initiatives to collectively reinforce food safety and address the topic flexibly to ensure its adoption and effectiveness. These extend beyond redesigning the process, to fundamental decisions about sourcing and the establishment of more collaborative specifications based on greater information transparency. New IT tools and collaborative platforms have made this possible.

According to economic theory, market forces do not necessarily serve the public interest. Traditionally, food supply chains have been characterised by arms-length, even adversarial, relationships between the different players. There has been little history of information sharing, either with suppliers or customers. In recent years, this has changed; the food industry can show good examples of collaboration between manufacturers and retailers in the form of planning, forecasting replenishment, and programmes such as the Global Food Safety Initiative (GFSI).

The underlying principle of collaborative working in the supply chain is that information exchange can reduce uncertainty. Thus, a key priority for food supply chain risk reduction is the creation of a food community to enable the exchange of information. The aim has been to create a high level of intelligence in the supply chain in order to gain greater insights into attitudes to risk up and down the chain.

In the wake of food scares related to salmonella and BSE, for example, the passage of the Food Safety Act in 1990 was a major watershed event in the UK, one that foreshadowed future legislation at an EU level. Under this Act, any supplier of a branded product is responsible for the safety of that product. Also, all fresh produce sold in an unpackaged form is considered to bear the brand of the retailer. Accordingly, enforcement action can be taken against a wholesaler or retailer even if the offense was caused by other parties in the food chain (for example processors, food importers, overseas exporters). Both reputation and financial resources are at stake if firms fail to prove due diligence in detecting and preventing problems in the food chain.

In response to the legal requirement of due diligence, the first food-safety-specific private standards were created in the early 1990s. Following the creation of the ISO 9000 quality standard, the International Organization for Standardization (ISO) created the ISO 22000, first published in 2005, setting out the requirements for a food safety management system that can be certified. However it failed to entirely meet the requirements of existing food standards. As a result the Food Safety System Certification 22000 (FSSC 22000) was developed, based on ISO and other standards, and the scheme is recognised by the GFSI. Various other standards followed.

The convergence of requirements aligned with the Codex Alimentarius standards has contributed to the widespread development of food audits and food safety certification schemes all around the world. This audit industry is now hampered in its capacity to serve the food supply chain by a certain lack of transparency but, more than anything, by the lack of auditors capable of meeting the requirements of demanding standards. More trained auditors are needed.

It is also worth mentioning that audits are a cost burden on businesses. There has been a proliferation of private industry standards that add costs but do not always benefit the producer or the consumer and ensure compliance of suppliers.

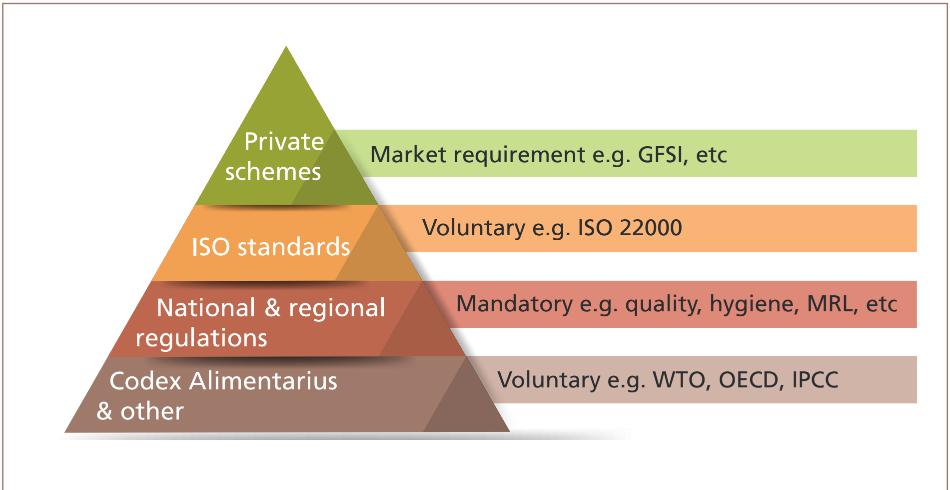


Figure 2: Pyramid of food safety schemes and standards

Consumers and food safety

The public perception of risk is usually very high when it comes to food; many consumers have a good understanding and know what they want in terms of health and nutrition of specific produce and products. A recent study from EFSA[16] of consumer perception of food-related risks found that 48% were worried that food may damage their health (up from 42% in 2005,) while 68% were worried about the quality and freshness of food and 51% disagreed that 'food today is safer than 10 years ago'.

Food safety is an emotional topic for many, giving rise to sometimes irrational decisions by groups or individuals which is made worse by social media, creating significant risk for food brands and the sector as a whole. In 2011, the German health authorities, without receiving complete results from pending tests, incorrectly linked an outbreak of E. coli in northern Germany to cucumbers imported from Spain. Consumer concerns about the outbreak were spread over social media. Although it was determined that Spanish greenhouses were not the source of the E. coli, the mis-reporting cost Spanish exporters US$200 million per week and Russia banned the import of all fresh vegetables from the EU for almost one month. The Spanish cucumber case illustrates the viral nature of social media and the impact it can have.

Many forward thinking organisations serving the food sector see social media as an opportunity to change consumer perception of the food industry. Some big brands have recruited hundreds of dedicated staff to monitor and influence discussions on social media. They recognise they have a role to play in defining what is true or fake in online forums and helping to ensure they keep their brand – and consumers – safe. It is a huge opportunity for consumers as well because people now have direct access to these organisations, and the entire food industry, to express their concerns about food safety, food fraud and other related issues. Consumers do not only expect their food to be safe, they also expect it to be healthy, of good quality, responsibly sourced, 'free from' (pesticides, GMOs, animal abuse, etc.), organic, vegan, fair trade and other attributes.

The sustainability and ethics of food production is of growing concern to consumers, who are paying more attention to issues including environmental sustainability and animal welfare. These concerns show themselves in dietary choices such as vegetarianism and veganism, and product choices such as organic, alternative protein and even meat and milk cultured in a laboratory.

Consumer trust in food is currently low even in developed economies. High profile food fraud cases, such as the UK/European horsemeat scandal of 2013 and Italy's 2015 olive oil scandal[17], have played a role in declining trust.

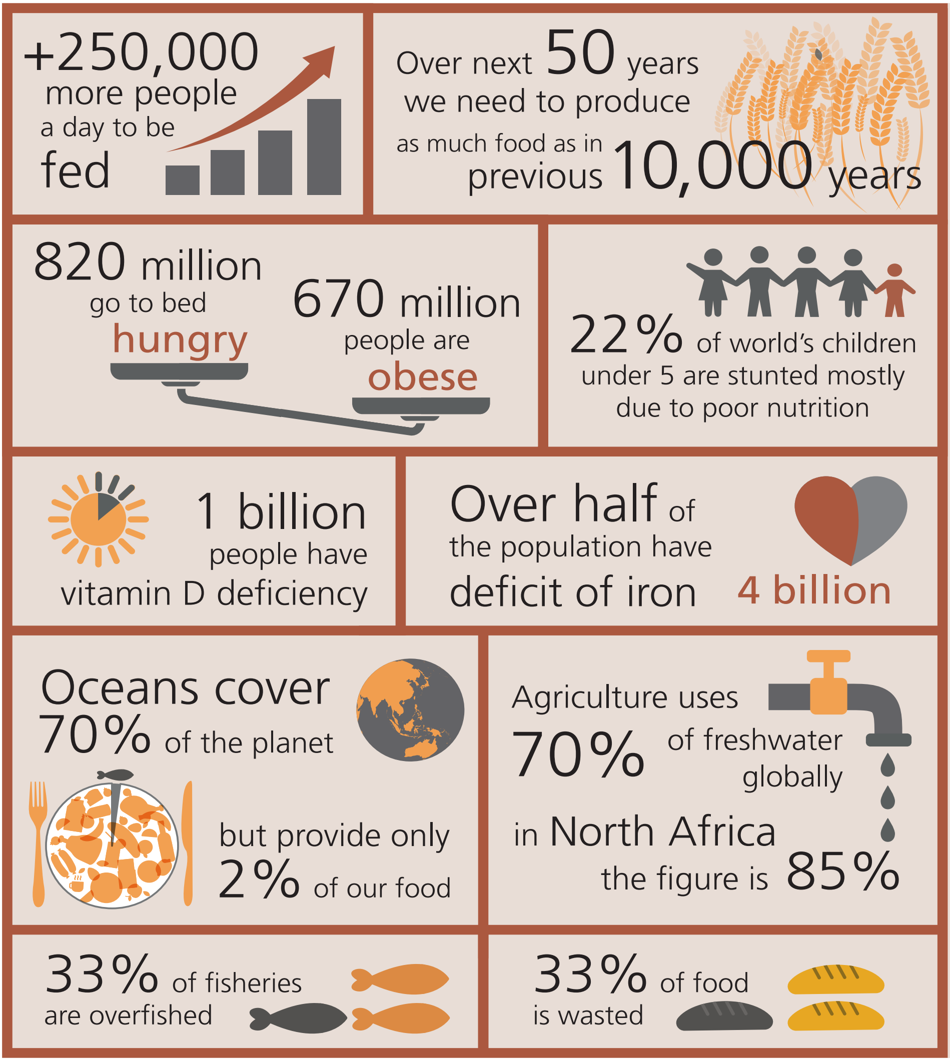
The market is confused by the fact that in the 1980s and 1990s there was a massive push towards low-fat diets to curb the growth of obesity. While most consumers followed the logic of the argument – you should eat less fat to reduce obesity – the trend was not stopped and, in some cases, even accelerated, likely due to the fact that in order to preserve the taste of food, more sugar was added. We are now trying to make consumers realise that sugar is probably the cause of obesity, but the industry has lost a lot of the credibility it once had. This has created many sceptic consumers, looking for their own solutions and guidance from 'citizen scientists' who, while they have good intentions, may lack the training to know the difference between hype and fact.

Food anxieties are associated with food security (for example rise of food banks and other forms of food aid), food safety (for example adulteration and food crime), food quality (for example UK consumer attitudes towards imported chicken and prawns), food hygiene (for example UK Food Standards Agency advice on washing poultry), food labelling and waste (for example ‘best before’ labels) and public concerns about technical innovation in agriculture or processing (for example genetically modified or irradiated foods). Although some consumers are very well informed, the majority have a limited understanding of issues and technologies, including the complexities of the food supply chain.

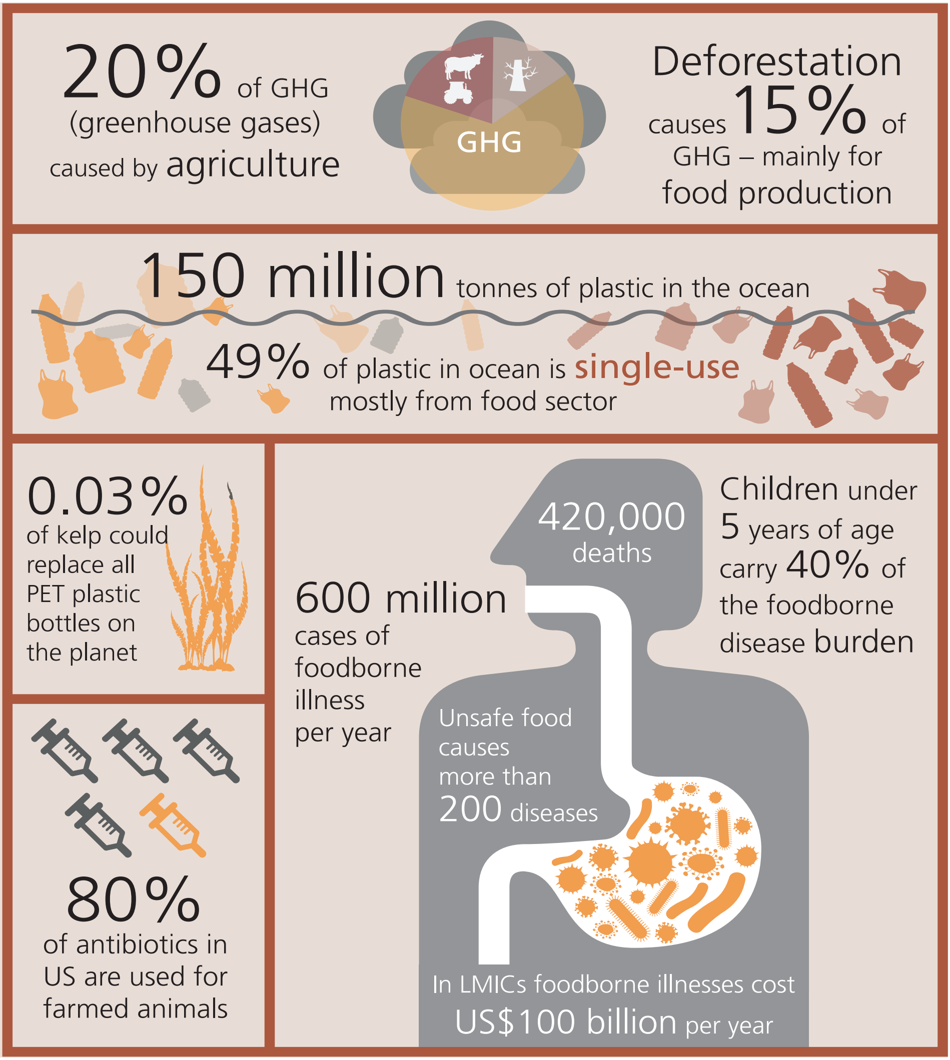
Food anxieties and perceptions tend to vary geographically and over time. Chemical preservatives went from being triumphs of modern science to poisons. Public attitudes towards whole milk have swung back and forth like a pendulum. Processed foods went from bringing healthy variety to the table, to being devoid of nutrients. Prime rib of beef was transformed from the pride of the American table into a cardiac disease risk and a contributor to climate change. The 'Big Fat Surprise'[18] is that saturated fats are no longer the risks they were once thought to be. Margarine went from ‘heart-healthy’ to artery clogging, while salt, historically regarded as absolutely essential to human existence, is “swinging the grim reaper’s scythe”[19].

Public attitudes towards whole milk have swung back and forth like a pendulum.

Food facts and figures



Using most recent statistics. For sources see references: 2, 20, 21, 22, 23, 24, 25, 26, 27


20% of GHG
(greenhouse gases)
caused by agriculture
GHG
Deforestation
causes 15% of
GHG – mainly for
food production
150 million tonnes of plastic in the ocean
49% of plastic in ocean is single-use
mostly from food sector
0.03%
of kelp could
replace all
PET plastic
bottles on
the planet
80%
of antibiotics in
US are used for
farmed animals
420,000
deaths
Children under
5 years of age
carry 40% of
the foodborne
disease burden
600 million
cases of
foodborne
illness
per year
Unsafe food
causes
more than
200 diseases
In LMICs foodborne illnesses cost
US$100 billion per year

Limitations of the current food supply chain and their impact on food safety

The food supply chain extends worldwide and is affected by multiple factors including the complexity of the system, the need to preserve food during transportation and sale, the role of investment in the food sector, fast growing demand, and the issues of food waste and lack of training and education. These limitations have consequences for food safety.

Complex supply chains and lack of traceability

Food supply chains are global and highly fragmented with multiple small stakeholders, often with no barriers to entry, allowing anyone to produce food for networks, especially domestically. Of all the supply chains, food supply chains are the most complex, and the fragmented markets that subsequently arise can result in low levels of transparency.

The larger food brands have a good understanding of their closest tier one suppliers, but tier two becomes more complicated to monitor and tier three can have up to 20 different, distributed layers. This results in a lack of transparency and traceability across the entire food supply network (see figure 8 on page 65).

Food supply chains are highly international, transporting various commodities and processed food around the world, creating a complex, multi-layered network rather than a traditional straight-line supply chain. Most food production and processing is carried out in a single geographic location to keep costs low. Food is then shipped and re-processed internationally, although a significant portion of raw materials and ingredients are shipped internally for further processing.

The corresponding volume of imports in each country contributes to the risk of foodborne illness, simply because it is challenging to oversee this level of diverse activity. According to the US Food & Drug Administration (FDA), some 94% of seafood consumed in the US is imported, 55% of fresh fruit and about 32% of vegetables are imported[28].

Food fraud and a lack of traceability are direct consequences of a complex food supply chain. Where there is a strong demand, compounded by a lack of supply or exchange rate differences, inevitably – and regrettably – there is a strong incentive for food fraud. The statistics alone give significant cause for concern. For example, every year, five times more virgin olive oil is exported from Italy than the country could actually produce and it is known that globally 30% of fish are incorrectly labelled. The oft-cited Grocery Manufacturers Association's Consumer Product Fraud Report (2010)[29] details a fraud rate of more than 10% of products sold in the US.

A lack of traceability throughout the food supply chain not only frustrates consumers' abilities to understand the authenticity of what they are buying, it also creates a challenging environment for companies. Actors throughout the food supply chain who want to respond to consumer demands and improve food safety must compete against opaque companies and corner-cutting practices. Traceability can help well-intentioned companies stay in business and protect their revenues.

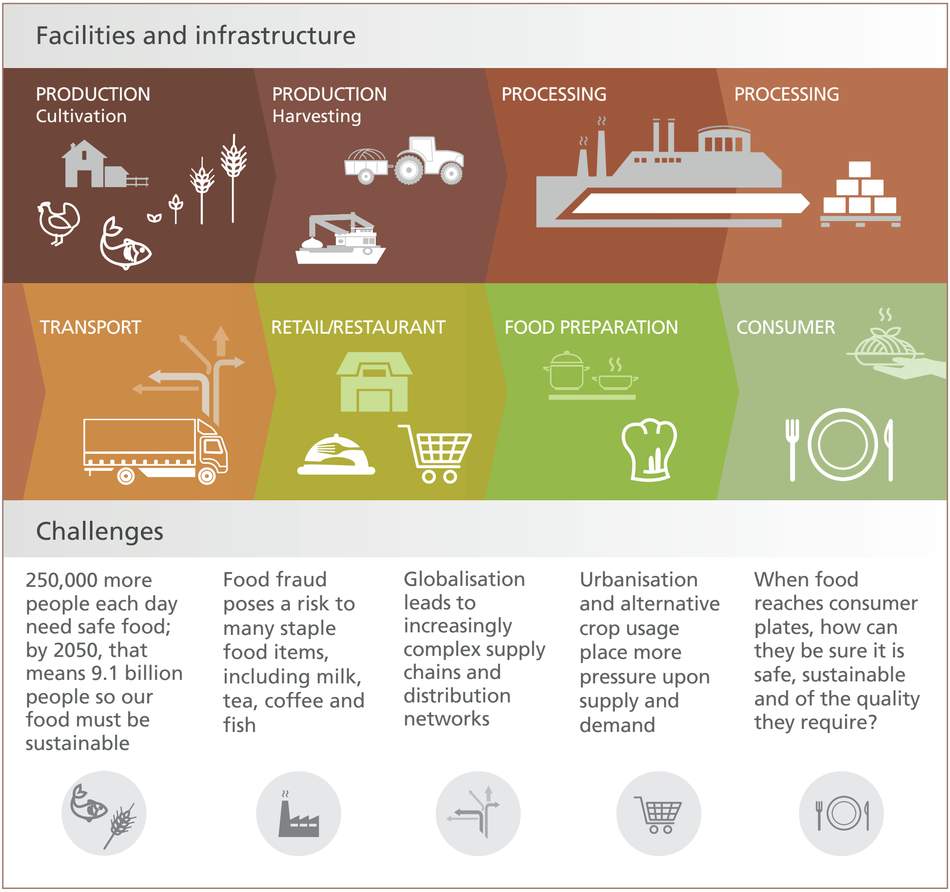


Figure 3: Complexity and challenges of global food supply chains

Preserving food safety – costs to the environment

Achieving food safety can have related environmental costs as food is transported, stored and displayed for sale. Two areas of current concern are plastic packaging and refrigeration required in the cold food chain.

Packaging: the plastic addiction

More than 150 million tonnes of plastic products can be found in our oceans today. Plastics make up 85% of beach litter worldwide[25], 61% of which are single-use plastics mostly linked to the food industry such as crisp packets, sweet wrappers, containers and disposable cutlery.

They pose a physical and toxicological threat to wildlife and to humans. Plastic decomposes into ever smaller pieces becoming microplastic. These tiny fragments disperse in the marine ecosystem including in fish. Some recommend that we eat more seafood and less meat, yet fish are increasingly likely to ingest plastic – a physical as well as a chemical hazard as plastic can adsorb toxic contaminants and then be carried into living organisms.

The global aquaculture industry is growing by close to 9% every year. By eating more fish, however, people could be ingesting more plastic. Plastic fibres and particles have been found in bottled and tap water and even in the air, settling on plates – evidence that the environment is filling up with plastic. People's health could be compromised: the chances of eating plastic are increasing and the consequences could be unprecedented.

The search for alternatives to plastic is an area of emerging research, but going plastic free is not a viable option at present. From airtight wraps to containers, plastic packaging brings the benefits of convenience, labelling information, traceability and tamper indication. But, most importantly, plastic packaging plays a key role in enabling a safe food system. Its main role is to protect food products from external influences and damage, and extend freshness and shelf-life. It limits food waste by preserving food at its best at each stage of the food supply chain. The longer a food item stays fresh, the greater its chance of being eaten. Studies have shown that bananas wrapped in plastic last 20 days longer than their unwrapped counterparts and beef wrapped in plastic vacuum packaging lasts almost 30 days longer. The reason plastic is the most used type of packaging is because the applications are so diverse. Plastic has supported a food system that has been essential in providing safe food with extended shelf life, especially during a period of rapid food demand and population growth.

Many food companies pledge to increase the amount of recycled plastic they use, or invest in the development of more sustainable options. Food packaging is among the most recycled packaging with recycling rates increasing every year. Yet bottles and their lids account for around one fifth of all plastic found in the ocean, according to EU reports. The European Parliament recently voted for a complete ban on a range of single-use plastics in all member countries in a bid to limit ocean pollution, and hopes this legislation will come into effect in three years. This is a great start but includes single use plastics with readily available alternatives such as paper straws and cardboard containers. Plastic reduction is much more difficult to achieve when alternatives do not exist such as for sandwich wrappers and meat packaging. Even tried and tested alternatives pose challenges. Producing drinks in glass bottles, for example, costs around the same as plastic bottles but boosts transportation costs significantly.

Then there is the issue of food waste. Plastic packaging can triple the shelf life of more perishable products, leading some to believe that doing away with plastic packaging will lead to greater food waste. The plastics manufacturers' association, Plastics Europe, also estimates that using existing alternative materials in place of plastic packaging would almost triple the amount of GHGs attributed to the food packaging sector.

Plastic is undoubtedly a challenge for those working in the food supply chain. Food industry giants have joined forces with recycling specialists to unveil new global services designed to enable household collection of empty or used product packaging for refilling, reusing or recycling. But consumers – partly as a result of popular television programmes like the BBC's The Blue Planet – are becoming increasingly reluctant to buy food packaged in plastic at all. While plastic alternatives remain expensive and difficult to source, companies continue to face a challenge. Viable solutions are desperately needed, and fast. Alginate and plant-based materials such as mushrooms and seaweed are being researched as alternatives to plastic bottles and food containers, even new packaging made out of a biodegradable 'microbiome'. New alternative innovations offer hope but bringing them to large-scale production will depend on better cost and production efficiencies, increased pressure from the public and, possibly, a change in legislation.

The plastics' issue is driving remarkable innovation within the food and drinks sector. Start-ups have been developing labelling systems that 'engrave' information on vegetables, eliminating the need for stickers or packaging. Others have developed tomato packaging made from dried tomato vines as it is widely recyclable and compostable. Others have created an 'edible water ball' made of a natural, biodegradable membrane from seaweed that can be swallowed and digested. Eradicating excess plastic from products will be easier for some companies than others. Some brands, for example, have switched to 100% aluminium pods for coffee makers. A California start-up uses bacteria to turn food or crop waste into a packaging material called polyhydroxyalkanoates (PHA), a biodegradable bioplastic, which is food safe, compostable and, should it end up in the ocean, safely degrades to become fish food.

Cold chain: a benefit and a threat

With nearly 1.6 billion domestic and commercial refrigerators, more than 1.3 billion air conditioning units and 552 million square meters of refrigerated warehouse[30], food cold chains are an important part of food safety, but they are also a contributor to energy consumption and, therefore, global warming. Although cutting-edge refrigeration technologies enable improved energy efficiency, they need significant investments. They also pose safety challenges due to flammability, pressurised equipment, explosiveness and toxicity.

The development of cold-chain technology was a major driver of food system innovation in the 1950s and 1960s, enabling the widespread consumption of fresh as opposed to tinned and dry food. Cold chain has also been key to addressing the issue of foodborne diseases. A WHO study highlighted that cold chain improvements cut the number of stomach cancers in the US by 90% between 1930 and 1990[31].

Cold chain also plays a major role in addressing food waste. There is a strong correlation between the amount of cold chain equipment in a country and its level of food waste: developed countries have 10 times more equipment than LMICs and three times less food waste.

Nevertheless, the challenges of cold chain are numerous:

- Temperature: dealing with a variety of products with various temperature ranges, very deep frozen (less than 60°C), fragile products (0°C-2°C), chilled products
- Cold chain performance: ensuring continuity, safety, security and traceability

- Environmental impact and the UN SDG roadmap: the need to tackle global warming (high global warming potential (GWP) refrigerants), improving energy efficiency, ensuring safety (pressured equipment, flammability, explosivity, toxicity); eight SDGs are directly linked to cold chain issues
- Qualification and certification: define standards (standards, testing protocols, certification schemes) and specific certification schemes (for example CERTICOLD).

For those working in the food supply chain, refrigerants pose a challenge, being both a benefit to food safety but also having a negative impact on energy consumption and, therefore, the environment. Yet, so far, cold chain remains an essential part of preserving food safety. More energy efficient alternatives are needed.

	World	Developed countries (DC)	LMICs	DC:LMIC
Population in 2009 (billion)	6.83	1.23	5.60	1:4
Cold storage volume (m^3/1,000 inhabitants)	52.00	200.00	19.00	10:1
No. of temperature controlled equipment for transport (million)	4.00	2.73	1.27	2:1
No. of people for each temperature controlled equipment for transport	1,708	450	4,421	1:10
No. of domestic refrigerators (per 1,000 people)	172	627	70	9:1
Food losses, all products (%)	25	10	28	1:3
Fruits and vegetables losses (%)	35	15	40	1:3
Losses of perishable goods due to lack of cold (%)	20	9	23	1:3

Table 1: Correlation between amount of cold chain equipment and level of food waste[32]

The changing role of investment in the food sector

Historically, governments have made major investments in agricultural productivity in order to keep food affordable and available. This has led to a reduction in the portion of income spent on food as incomes rise, so that consumers now spend less than 10% on food in most developed countries. Yet, even though the share is declining, wealthier consumers spend a larger total amount on food over time. In high income countries, these expenditures have supported a larger food service sector and expanded demand for quality and variety in food markets. This process of food system transformation is now well underway in middle income countries and is reinforced through evolving e-commerce channels for food.

The global private industry investment in agricultural research and development (R&D) in 2014 was US$15.6 billion. This includes research investments in crop and animal production, which supports global growth in productivity. Investments in R&D for the food system post-farm gate (after food products have left the farm) by the food industry were over $18 billion in 2012 (the most recent year for which data are available)[33]. The graph below reflects trends since 2000 in both kinds of R&D. Research has been focused on new product development or improved processing methods, including enhanced food safety. The amount spent by the industry on R&D has more than doubled since 2002 in nominal US dollars, growing from about $7 billion to over $18 billion. Although most investment is still found in developed countries, LMIC food research has increased in recent years, particularly in China.

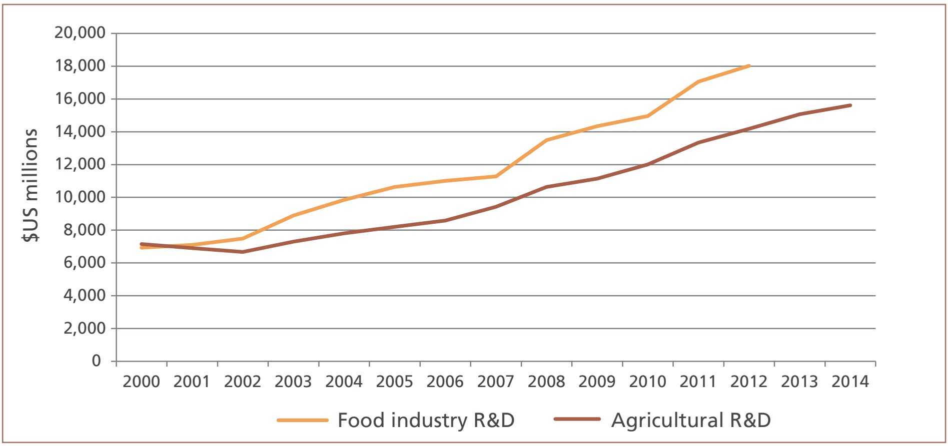


Figure 4: Private sector R&D expenditures for food and agriculture worldwide, 2000–2014[33]

The global research intensity of investment in food, however, is low relative to other industries. According to the University of Surrey, for example, the US only allocates 3% of its R&D funding to the food industry but over 10% to many other major industries.

A relatively new source of funding for food innovation is emerging from venture capital firms and impact investors that are investing in the development of new food technologies[33]. For example, in 2014-15, US venture capital funding included $2 billion for food e-commerce and a total of $884 million for food manufacturing technologies, food safety and traceability, novel methods of producing protein foods and waste technology. These kinds of investments have the potential to transform approaches to food safety.

More recent information reinforces that this is a continuing trend. In 2017, venture capital firms spent billions of dollars on the internet of food (alternative market delivery) and on food innovations, including alternatives to sugar and animal proteins, and hundreds of millions on food safety and preservation, and on personalised nutrition[34]. Nevertheless, there are millions of poor and vulnerable farmers in low income countries, where investments in agriculture and food systems lag behind addressing critical needs for efficiencies and higher productivity. According to venture capital company Unigrains, while public global investment in agricultural R&D surged with the food crisis of 2008, it has since levelled off. Increased public and private investment will be needed to address chronic under-nutrition in low income countries.

Another issue is low income and margins; food needs to be affordable. Government and authorities are careful to ensure affordable food prices as any rise in major commodities can quickly lead to severe social tension or even riots. In Western Europe, the portion of household income dedicated to food has reduced from 25% to 8% in 40 years, while other household expenses (for example energy and housing) have increased and new ones have emerged (for example communications, IT and tourism). People are not ready to pay incremental price increases for food.

This, in turn, creates a problem for those working throughout the food supply chain. Food prices are declining or remaining the same, which is bad news for farmers all around the world, many of whom struggle to make a living out of their production. To put this into context, out of the 795 million people who went hungry in 2015, 600 million of them lived in rural areas, largely depending on farming[35]. The very people who can and should produce food are the ones who are starving.

Further along the food supply chain, food companies also face challenges. Food is high risk and low margin and, therefore, attracts low levels of investment. Companies must compete for investment against other industries that have bigger margins and better returns. This makes investment in food safety more difficult. Furthermore, consumers want better food safety but are sometimes unable or unwilling to pay increased food prices; food is, after all, a basic need. This puts pressure on companies to adapt but with little room to put up prices. In a nutshell, the industry lacks adequate investment to make food safe and traceable.

Fast-growing demand for food production

Considering the mega trends within the food sector, with a particular emphasis on the significance of population growth, many other limiting factors will affect our ability to feed ourselves in the future, and this has implications for food safety:

- We have almost used up the planet's available arable land
- A portion of food and feed crops are being converted to biofuel
- Crop yields have been declining for many years
- Diets are shifting to become more westernised with increases in meat consumption expected to continue, which multiplies the calorie demand by 10 compared to the growth of the population
- 820 million people go to bed hungry every night; this number has been growing over the last four years[36].

If the current global population were to consume the same level of meat as Europe, five planets covered with grazing land – ocean included – would be needed. Various studies show that in the next 50 years the supply chain must produce as much food as has already been produced over the last 10,000 years[20].

Furthermore, intensive monoculture farming (the growing of one crop species) and the containment of livestock have depleted soils of their essential elements. When soil – a vital resource – is not exposed to the kind of replenishment provided by sustainable agriculture and natural fertilisation by free range livestock, we lose our ability to grow more food.

Fast-growing food demand coupled with depleted agricultural resources pose a serious challenge to global food security, but this demand also presents a challenge to food safety, especially to those working in the food supply chain. Companies that address food safety concerns will, unfortunately, find themselves competing with companies that are shielded by a lack of traceability in the supply chain. Take, for example, watered-down milk. While demand for milk remains high, but costs stay low, disreputable companies can exploit consumers with promises of authenticity while not providing it. The lack of accountability and traceability creates an environment for food fraud. Growing food demand also puts pressure on companies to act more quickly. It can make food supply chains bigger and more complex, creating challenges for visibility into the chain, including into ethics and safety, which is why new technologies offer so much potential.

Food waste and loss, and the circular economy

Disturbingly, while food demand is increasing and agricultural resources are being depleted, food waste and food loss remain too high. One-third of all food produced in the world – approximately 1.3 billion tonnes – is lost or wasted every year. Sixty-six thousand kilogrammes of edible food is wasted every second[37]. Developed and emerging economies contribute to food loss and waste equally, with emerging economies affected more by food loss, and developed ones more by food waste. Globally, if food waste could be represented as its own country, it would be the third largest GHG emitter behind China and the US. The resources needed to produce the food that becomes lost or wasted has a carbon footprint of about 3.3 billion tonnes of CO_2[38].

In the US alone, some 60 billion kilogrammes of edible food (worth over US$161 billion) goes to waste every year. Food waste also contributes to the largest volume of material in US landfills accounting for 21% of the waste stream. Per capita waste by consumers ranges between 95-115 kilogrammes per year in Europe and North America (consumers in sub-Saharan Africa and South/Southeast Asia each throw away only 6-11 kilogrammes a year)[39].

Reducing both food loss and food waste would lead to more efficient land use and better water resource management with positive impacts on climate change, livelihoods and food security challenges. Target 12.3 of the UN SDGs aims to halve food waste by 2030.

A coalition of governments, businesses and civil society dedicated to reducing food waste, recently launched the Food Loss and Waste Accounting and Reporting Standard in partnership with leading organisations. This represents the first set of reporting requirements for companies and governments to quantify and report on food loss and waste in order to develop targeted reduction strategies.

Food loss refers to any food that is lost in the supply chain between the producer and the market. This may be the result of pre-harvest problems, such as pest infestations, or problems in harvesting, handling, storage, packing or transportation. Some of the underlying causes of food loss include the inadequacy of infrastructure, markets, price mechanisms or even the lack of legal frameworks.

Food waste refers to the discarding or alternative (non-food) use of food that is safe and nutritious for human consumption. Food is wasted in many ways. Fresh produce that deviates from what is considered optimal in terms of shape, size and colour, for example, is often removed from the supply chain during sorting. Foods that are close to, at or beyond the 'best-before' date are often discarded by retailers. Large quantities of wholesome edible food are often unused or left over and discarded from household kitchens and eating establishments.

Embedding circular food economy principles, with all products and by-products either eaten, composted or 'otherwise valorised' (given a price or value), within the global agri-food sector could contribute US$2.7 trillion to the global economy through decreased healthcare and environmental restoration costs[40]. In cities, less than 2% of the valuable biological nutrients in food by-products and organic waste (excluding manure) is composted or upcycled[40]. Ensuring true circularity within urban food systems will require unprecedented collaboration between food brands, producers, retailers, city governments and waste managers.

Cities can play an important role in sparking a shift to a fundamentally different food system in which we move beyond simply reducing avoidable food waste to designing out the concept of waste altogether. As the place where most food eventually ends up, cities can ensure inevitable by-products are used at their highest value, transforming them into new products ranging from organic fertilisers and biomaterials to medicines and bioenergy. Rather than a final destination for food, cities can become centres where food by-products are transformed into a broad array of valuable materials, driving new revenue streams in a thriving bio-economy.

One recent example is the award-winning Circular Food Economy Project in Canada developed by the City of Guelph and County of Wellington. Guelph-Wellington aims to bring its food system and communities back into healthy balance. Leveraging local expertise, big data and the latest technology, it will transform its food ecosystem into an 'urban/rural living lab' where researchers, social innovators, farmers, entrepreneurs and other community partners collaborate to solve complex food problems. It aims to enhance access to nutritious food, turn 'waste' into valuable resources and create new economic opportunities[41]. It is interesting to note that the City of Guelph, together with the Region of Waterloo in Canada, were the originators of the 'blue box' recycling system in the early 1980s[42].

Upcycling brewing industry by-product

Brewers' spent grain (BSG) is a by-product of the brewing industry rich in proteins and sugars. It constitutes 85% of the by-product generated by breweries. In 2015, nine billion kilogrammes were generated throughout the world but, today, most of it is still discarded. Through fermentation it is possible to upcycle BSG and create a new kind of food full of antioxidants, proteins and vitamins (B1 and B2), which can be used in other products. Instead of wasting this food we can transform it into a nutritious, useful product, suitable for example, as animal feed[43].

The new food business model should also develop products and recipes that use food by-products as ingredients and that avoid certain additives to be safely returned to the soil or given a value in the wider bio-economy. In this way food designers can play their part in designing out food waste. Marketing can position these products as easy and accessible choices for people on a daily basis. There is a need to provide 'better for you' plant-based food options (more nutritious, healthier and tastier) to reduce dependence on animal protein. Smart fermentation is the next green food process. New tools and processes are needed to naturally enhance the nutrition and taste of food and upcycle by-products into high value ingredients or upcycle biomasses from waste to nutritious food. The process is comparable to safe food fermentation where a microbe is able to live on and digest a food for fermentation without impacting food safety – the original bio-technology.

At the macro scale, food loss and waste pose a serious challenge to global food security. At the micro scale, they also signify a challenge to companies in the food supply chain. They are the costs of an inefficient system. Where inefficiencies can be tackled, more energy can be spent addressing food safety.

Lack of education and training in food safety

A lack of education and training in food safety puts a strain on the global food supply chain and this is a challenge for the industry. Across the board, from consumers and government officials, to food auditors and industry experts, education and training are important tools in helping people make evidence-based decisions in food safety.

At a consumer level, a lack of education about food safety has had a cumulative impact with generations tackling health issues such as obesity. Consumers often talk about mixed messages around food safety and nutrition. Can they eat food beyond its sell-by date? Should they not eat certain types of fat? One week, they are told to eat some red meat, next week, they are told all red meat is bad for them. Consumers are confused and need more evidence-based information but also more education around food safety in general, in order to be able to make their own informed decisions.

At a governmental level, when it comes to making funding decisions, for example, more education and training around the facts of food safety might help improve evidence-based investment in the sector. We often hear about the impact of major infectious diseases such as HIV/AIDS, malaria and tuberculosis on health and life-expectancy. Yet, studies have found the global burden of foodborne disease is comparable to these major infectious diseases. Greater education and training in food safety would help raise awareness about this.

With regard to plastics, education and training are essential, especially in terms of understanding definitions and implementing regulations. Navigating the existing packaging regulations at national and international levels (EU, UN) is a real concern for innovation as well as enforcing new regulations for plastic reduction in emerging economies. Public education around plastic is important.

The complexity of a circular food economy is difficult to communicate, requiring close collaboration with local communities, NGOs, regulators and large brands to raise awareness and commitment to this fundamental principle of sustainability.

In relation to cold chain, recent innovations such as new refrigerants with lower GWP, natural refrigerants, or development of new technologies based on absorption systems will help to address the challenges; but education of policy makers, managers and technicians is also key to ensuring a performing and resilient cold chain. Eventually, the implementation of solid networks of experienced private stakeholders and strong political support in each country should play a key role in the establishment of an efficient cold chain to secure the food systems of tomorrow.

Lack of food safety knowledge and skills is a challenge for everyone. Consumers need more information about the food they eat. Companies need greater skills and training to provide this information.

Technologies and trends to shape a new food safety system: New technologies in life science

Historically, technology investments in food have been hampered by low margins and the need to keep food affordable. Consequently, technology and data science innovations have been limited in the industry so far.

Now the situation is changing and, driven by more demanding clients, data science and life science are about to converge to shape a new model for food safety. The next three sections explore some of the most important topics that contribute to this change, starting with life science technologies.

More traceable and sustainable food production and protein

One of the strongest conclusions we can draw from the challenges outlined in the previous section is that food safety relies on traceability and sustainability, and that the two are linked. Traceability is essential to safe food production, but any traceability built into the food supply chain must be sustainable. There is simply no point investing in a safe food production system if it cannot be sustained.

Meat protein: lab meat and insects

Let us start by looking at meat production because this is an area where, if both traceability and sustainability can be addressed with new technology, we will see radical improvements to the food supply chain and, therefore, to food safety. Meat is one of the less traceable foods in the supply chain and this has implications for food safety. Meat can be contaminated in slaughterhouses and overuse of antibiotics in livestock can cause bacterial resistance to superbugs in humans.

Furthermore, meat production is not an efficient form of human feed. It takes 23 calories of crops to produce one calorie of beef. This is the so-called conversion ratio. It is high for cattle and a little lower for pigs and chicken. In a nutshell, many resources are lost when livestock are used as an intermediary for human feed.

To add to the sustainability problem, demand for meat is predicted to double by 2050, meaning greater use of precious natural resources. Currently, livestock take up 70% of arable land. If every human on the planet ate as much meat as Europeans do currently, we would need five planet Earths covered entirely by grazing land.

Furthermore, livestock contribute 15-20% of GHG emissions. For cows this is primarily methane, which is 20 times more potent than CO_2. They also use a lot of water: 15,000 litres of water are needed to produce one kilogramme of meat. For rice or soya, it is only 2,000 litres.

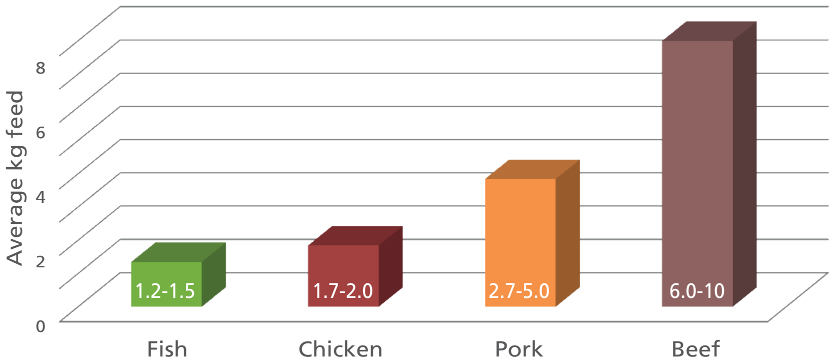


Figure 5: Feed conversion ratio for farm-raised salmon, pork, chicken and beef showing the number of kilogrammes of feed needed to increase the animal's bodyweight by 1 kg[44]

Lab meat

Cultured or lab meat is meat produced when animal cells are cultivated in a dish (in vitro). A small piece of muscle is taken from a cow through a biopsy. Under the right conditions, stem cells found close to skeletal muscle cells divide and produce new muscle fibres outside the body. The muscle cells merge to form a primitive muscle and then grow around a central hub of gel attaching to each other as a true muscle.

This technology has the potential to produce animal proteins in a cleaner, more ethical and more sustainable way. Lab meat may also offer health benefits through reduced exposure to potential contaminants and may help combat antimicrobial resistance by reducing the use of antibiotics in animal husbandry.

Initial samples are usually small, which helps to reduce the likelihood of disease. The original material is easily traceable and the process is sterile, so diseases and pathogens cannot be introduced. In terms of efficiency and sustainability, preliminary life cycle analyses show substantial reductions in the resources needed to culture beef. Research from the University of Oxford indicates this technology could result in a 90% saving in land, a 90% saving in water and around a 60% saving in energy. There are also, of course, fewer methane emissions.

Currently, lab meat production still faces challenges. The process has not yet been optimised. Expensive biomaterials are needed to grow the cells, and many cells are needed for replication. The tissue formation process is automated, which involves complex machinery. It is also possible that consumers may not accept or embrace this approach to meat production.

Edible insects
As a form of food, there are several benefits to insects, including their high nutritional content. Besides fats and proteins, insects are also an excellent source of amino acids and vitamins for humans.

In terms of sustainability, insects have a greater food conversion efficiency compared to traditional farm animals: crickets need six times less feed than cattle, four times less feed than sheep, and half as much feed as chickens and pigs to produce the same amount of protein. They also produce lower ammonias and GHG emissions, need less land and water, and can be easily grown on organic waste.

The consumption of insects, therefore, contributes positively to environmental, food and nutritional security, and a healthy life for present and future generations. Over 200 companies worldwide are currently researching various types of insects for feed or insect food production.

Nevertheless, the low level of regulation for novel food in Europe and the US represents a major hurdle for the rapid development of insects for food. Also, technological improvements are needed in order to properly industrialise the production of insects, moving from 10 tonnes per day per factory to thousands of tonnes per day per factory.

Even through insects are genetically distant from humans – so few pathogens can be transmitted – some biosecurity and food security questions remain, mostly because this is a new area of food production and companies simply have less experience in and insights into intensive consumption of insects or livestock fed by insects.

Also, there are many social challenges when it comes to humans eating insects: overcoming the novelty, incorporation within existing cuisines, concerns about animal welfare, taste comparison with alternative sources of protein and price premium, for example.

Seafood protein: the blue revolution and offshore infrastructures

Aquaculture is the world's fastest-growing animal food-producing sector. The global growth is expected to continue to meet the estimated demand for an additional 40 billion kilogrammes of aquatic food by 2030, at the current per capita consumption.

Sustainable production practices are needed, including moving away from fish-based feeds, toward those based on plant products and environmentally-sensitive development that minimises impacts on coastal ecosystems. Intensive aquaculture needs technologies that reduce the risk of mass mortalities due to disease. These include rapid high-throughput, disease screening of hatchlings, enhanced selection for disease tolerance, production and distribution of better diets using more sustainable ingredients, and improved environmental management of production ponds and the surrounding environment. In salmon farms, for example, sea lice infestations have been known to kill juvenile fish, depleting stocks. Approaches such as biological control – the use of natural enemies to limit the spread of pests – have proved successful. A species of wrasse (a 'cleaner' fish that eat sea lice) has been introduced to salmon farms to help control lice pests and protect stocks.

While aquaculture in coastal areas is cost-effective in terms of operations, there are undesirable consequences for the environment, biodiversity (for example species loss, risk of mangrove extinction) and coastal communities. Indoor aquaculture, with intensive recirculating of water, limits some of the risks associated with outdoor aquaculture, and while they are more expensive, commercial land-based operations also exist such as for the production of salmon and rainbow trout. In addition, advances in technology and the use of aquaponic systems (systems that combine aquatic animals and plants) enable the culture of exotic species for those customers who want them.

Fish farming is on course to exceed the fishing sector within several years and could greatly enhance food security. Agriculture has been industrialised over the past 10,000 years, but it has never really focused on the ocean. While 70% of our planet is covered by ocean, it only contributes 2% of our food. There is a huge opportunity for development and growth, termed the blue revolution, which refers to a time of intense growth in the worldwide aquaculture industry from the mid-1960s to the present (aquaculture production has now reached 80 million tonnes, up from 0.6 million in 1950[45]). A similar growth in land-based agriculture in the 1960s and 1970s is commonly referred to as the green revolution.

Fish, shellfish, plant life and seaweed should all be considered viable alternatives to land-based protein sources. It is estimated that if just 2% of the oceans (an area roughly the size of Australia) were dedicated to growing and producing seaweed as a food source, enough protein could be produced for 12 billion people with no need for animal or vegetal proteins.

To reach its full scale, the blue revolution will have to go offshore, as coastal areas are already saturated with multiple activities. Moving production offshore offers valuable benefits including no competition with coastal or inshore areas, using fewer inputs like antibiotics (the farming is less intensive and can take up more space, meaning diseases spread less easily) and increased distances between sites that could potentially limit exposure to diseases and parasites, like salmon lice, from neighbouring farms.

Yet, there are still serious challenges that include higher levels of investments relative to traditional aquaculture infrastructure, increased insurance costs due to operations in exposed conditions (sea current, waves and wind), and a lack of knowledge about the farmed species and their behaviour and welfare in rough environments.

Multi-use of the ocean for both production of energy (wind farms, for example) and food (such as finfish, mussels and seaweed) is increasingly perceived as an opportunity to industrialise food production at sea while optimising the cost of offshore production. It will require a better understanding of the benefits and risks for each type of production. Currently, projects have been launched by the EU and the US Department of Energy to pilot this approach through real use cases.

Ensuring safety of food, employees and infrastructure will be a challenge in such difficult conditions and remote areas as they are hard to reach and monitor. Work is being conducted, for example, on video technologies installed on under-audit platforms and vessels using a mixture of human and artificial intelligence (AI) to monitor activities and provide reports at the end of the audit period. This saves the need for people to travel offshore, gives evidence-based feedback and allows for repeat audits to take place that monitor improvements.

Local food for a more traceable and sustainable system

Urban farming and vertical farming

Since 80% of food will be consumed in cities by 2050, the cities can significantly affect the way food is grown, particularly by interaction with producers located at the edges of cities and towns. Indoor and urban approaches to growing food can be highly dependent on energy production, for example, growing vegetables in containers requires LED lights powered by solar panels. But they also have the potential to be optimised for safety and sustainability through limiting transportation, full control of the environment and inputs (for example seeds and soil), better water consumption (99% less water used) and incorporation of AI approaches to maximise the plant development.

Uncertainty can be removed from growing food, managing the inputs to maximise the outputs or yield. By making the most of analytics and machine learning, we can harness large amounts of data collected by remote farming sensors and unlock opportunities to automate ways to drive higher yields. These trends, combined with trends in urban farming, will dramatically improve the efficiency of growing food in small places.

Cites cannot, of course, implement these techniques alone. Collaborating with farmers and rewarding them for adopting these approaches will be essential. In parallel, cities can use circular urban farming systems, where waste becomes input to a new process, such as those that combine indoor aquaculture with hydroponic vegetable production.

The benefits and feasibility of increasing local sourcing have been the subject of intense debate. While urban farming can provide cities with certain fruits and vegetables, it cannot currently fully satisfy people's broader nutritional needs.

More and more vertical farming projects are being developed to optimise land use and reproduce natural food ecosystems through so-called controlled environment agriculture (CEA). This is the process of growing food in vertically stacked layers within factory-style situations. CEA allows for faster, more controlled production, irrespective of season. One acre of vertical farming can produce the same as 10-20 acres of conventional farming. This approach means greater food security, since the controlled production is not vulnerable to variable factors such as climate, pathogens or pests. Furthermore, a vertical farm can take advantage of low-value land otherwise unavailable for food production.

There are three main systems used for CEA: aeroponics (growing plants in air or mist), aquaponics (growing animals and plants together in water) and hydroponics (growing plants in water). All three are systems for growing vegetation using nutrient-rich water solutions which the roots of plants can access directly rather than in soil.

Specific food safety challenges are associated with these new types of food production since they are very complicated (more complicated, for example, than car or computer production) and with variable factors that could allow a pathogen to grow. People involved in these kinds of new food production also generally lack experience and training in food safety best practices.

3D printing (additive manufacturing)

Additive manufacturing of food is a young field with great potential but limited application. The key motivators for 3D printing food are customisation, on-demand production and geometric complexity. A good example of this is the reproduction of traditional foods, such as pizza, using 3D printers. Methods for allowing the production of grain- and protein-based products, which have a stable shape throughout the cooking process, mean the shape remains accurate and true. Data-driven recipes allow for customised flavours and nutrition, and printing processes enable the production of unique textures. Together these advances create an important step toward developing novel uses of 3D food printing.

More and more 3D printing companies are becoming involved in food production but more in terms of food processing at home than new ways to cook. Some are already looking at taking useable food waste, such as tomatoes, and making powders from them, then printing the powders into something that can be used to produce food more sustainably.

Photo credit: Natural Machines

Printed food can help everyone create cheap, safe, traceable mass market versions of premium products. Raw ingredients, for example, can be printed into safe, sustainable, tasty products helping improve food supply chains through efficiency and reduce food waste, addressing all manner of sustainability issues. 3D printing could also help to solve other food-related issues, for example, the eating of insects or other unusual types of protein by redesigning their nutritional content into something that people would like to eat. Nevertheless, many food safety concerns are still to be clarified.

DNA verification and next-generation sequencing techniques

DNA (deoxyribonucleic acid) in animals and plants partly determines physical traits such as eye colour and resistance to diseases. An organism's DNA can be read through a method called DNA sequencing which enables exact identification of the organism and provides insights on its traits. Over the last decade, the technologies used to read DNA have significantly decreased in cost enabling many new applications including food safety.

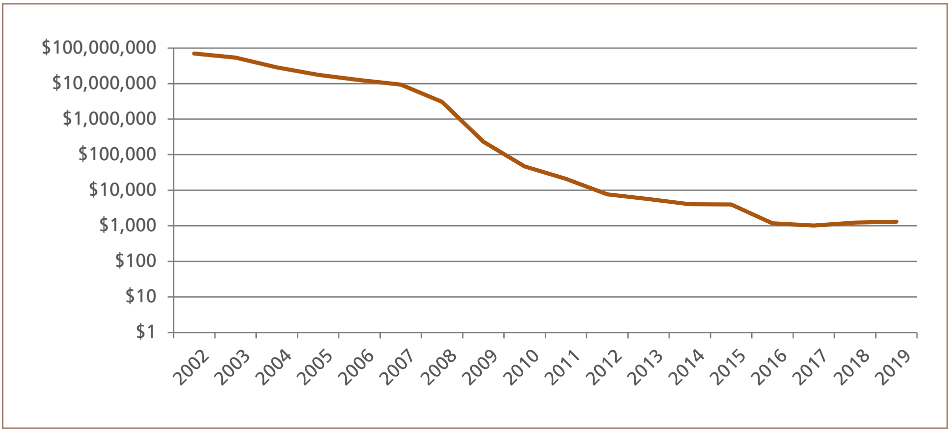


Figure 6: Sequencing cost per human genome - 2019[46]

Next-generation sequencing (NGS) platforms that power these readings use advanced databases and technologies to give a much faster DNA analysis. NGS platforms use something called DNA 'barcoding' to enable companies to test food samples and compare their content against the DNA of a particular allergen, ingredient or pathogen.

Scientists can even take a 'snapshot' of the entire DNA present in a given environment for deeper identification of a sample. Non-targeted whole genome sequencing (WGS) is used for this purpose. Many food manufacturing plants have standard decontamination processes to handle resident pathogens, but what happens if something unknown enters the facility? By looking at all of the genomic information in a given sample and comparing it to a database of genomic information on resident pathogens, WGS can quickly identify strains that the facility might not even have considered. Regulatory organisations are generally supportive of WGS applications: when WGS first emerged, the FDA stated it was the biggest thing since pasteurisation, but many challenges remain.

NGS analyses generate a large amount of data, which create challenges for access and storage. And there are legal issues around who accesses the data and how it can be used. NGS offers an unprecedented opportunity to protect against possible food threats, create high-quality databases for pathogens and customise internal reporting based on state-of-the-art science and good business practices. Those in the food industry know speed is of utmost importance, especially when addressing a contamination issue or recall. Identification of contamination using DNA sequencing is fast and specific, enabling identification of the exact microbial strain and helping pinpoint disease outbreaks.

NGS has several potential future applications in food safety. This includes monitoring foods for a more accurate estimate of shelf life (more accurate than the marked expiry date) and detecting food type and origin, which helps combat food fraud regardless of whether processing – filleting or mincing, for example – has altered its physical appearance.

Gene editing

In the last few years, new genome engineering tools have been developed that enable scientists to alter, add or remove genetic material from an organism with near complete precision. With these new tools, genetic manipulation can be performed faster and more accurately than ever before. Altering genetic material has historically been an expensive and uncertain process, but modern genome engineering techniques are relatively cheap, precise and powerful. Furthermore, their use is better guided by a growing understanding of genomes.

Perceptions and regulations about GM (genetically modified) food mostly focus on 'transgenic' crops, which are made by inserting genetic material from one species into another using non-precision editing processes. However, precision genome editing is now possible, for instance, with CRISPR/Cas9, or other systems. These are technologies that edit genomes. They bring about 'subgenic' rather than transgenic changes, that is to say they alter an organism's genetic material directly in a defined manner rather than incorporate another organism. As these subgenic alterations could occur naturally, they do not fall under GM regulations in some jurisdictions. The field is still emerging and there is no guarantee of widespread commercial success. Active debate around unintended side effects continues.

Microbiome, the bacteria revolution

So far, we have looked at ways to improve safety in food itself, but what if we look at the human body as the front line of food safety. Researchers are starting to see the gut microbiome as an important part of the food safety story, protecting you from foodborne diseases and beyond.

The microbiome is a community of beneficial microorganisms such as bacteria, fungi and viruses that inhabit particular environments including the human body. Each of us is home to about 100 trillion bacteria and other microbes, collectively known as our microbiome. This microbiome lives in our mouth and skin, but most of it resides in our gut where it is a key part of our interaction with food, playing an important role in metabolism.

Taken collectively, these organisms outnumber our own human cells to such an extent that we are 99% microbial when we look at our gene pool. Humankind has evolved with these bacteria, passed down from mother to child. It is now known that in early childhood development – as early as birth and even in the womb – the gut bacteria play an integral role in the formation of a strong human immune system. And scientists are now uncovering the significant role they play in the bigger food safety story.

Figure 7: Human genes, cells and microbiome

With developments in DNA sequencing, we can better understand the various compositions of microbiomes in our digestive track, invisible so far but known under the vague term of gut microbiome. Science is now capable understanding how this complex organism impacts life in general and more specifically, food safety.

We have been raised with a belief that bacteria are the enemy, responsible for illness and to be eradicated by taking antibiotics. But we are starting to realise that the pendulum has swung too far, and we are over-sanitising ourselves removing key protective bacteria from our skin and overusing antibiotics, which has led to the rise of many chronic diseases such as diabetes and obesity. The same over-sanitisation and over-reliance on antibiotics (in cattle, for example) has been observed in our food production.

It is now clear that in our fight against bacteria, we are also destroying beneficial ones essential to life and wellness. Since the early 2010s, we have been waking up to our neglect of 99% of our existing genes – the easily modified microbiomes. The connection between microbiomes and specific diseases such as cancer, diabetes and obesity is becoming increasingly obvious[47]. A better understanding of this connection will help us fight these diseases, potentially by eating certain foods: prebiotics (dietary fibre to boost reproduction of bacteria) or probiotics (living bacteria) or a combination of both.

Other research has examined the role that gut microbiome has on nutrition and weight. Gut bacteria are responsible for breaking down many of the complex molecules found in foods, such as meats and plants, into smaller molecules that our body is able to digest. Studies show that certain bacteria are associated with obesity and others with normal weight[48]: when lean mice are given the gut microbiome of an obese human, for example, they gain weight.

Research has also shown a direct relationship between diet and the abundance of certain gut microbial communities. For example, vegetarians have gut flora that are better equipped to break down plant roughage, making otherwise indigestible molecules such as cellulose digestible for humans. During bacterial metabolism of these complex molecules, chemical signals are released to our brains and can affect behaviour. This has led some scientists[49] to speculate that the gut microbiome may cause cravings for certain foods and influence dietary choices and may even affect everything from taste to mood.

Additionally, it is believed that diversity – the presence of many different bacteria – makes a healthy microbiome. Similarly, a diverse microbiome appears to be linked to the variety of plants that people consume. This seems to indicate that it is not necessarily the amount of plant in a diet that matters but the diversity of the plants consumed.

But the microbiome is not only found in the gut; it is everywhere. The idea that bacteria and dirt are good never seems to have been so accurate, as demonstrated by the fact that gardening increases your exposure to beneficial soil microbes, which can be linked ~ to increased happiness.

Conversely, the opposite is also true. While beneficial microbes can move around easily, so too can chemical pesticides, which are transferred from vegetable to human as early as in the store when the consumer selects them for purchase.

There is a strong link between depleted microbiomes and costs to society. In medicine, the societal cost of non-communicable diseases such as diabetes and obesity can be measured. It is now believed that the overuse of antibiotics and chemical pesticides have depleted the diversity of certain human microbiomes so much, they cannot produce any more molecules beneficial to good health, not just in the gut or mouth but at a holistic level. We now know that up to 25% of molecules measured in the blood come from the microbiome. The microbiome affects many parts of the body: it produces many neurotransmitters, fatty acids, polyphenols and even natural ‘medicines’. An organ-specific approach to medicine is being challenged. We need to embrace a more holistic approach where humans, their food and the environment form a fully interconnected system.

In future, there could not only be one normal healthy microbiome profile but many represented all over the planet based on our various genomic background and diets. In the same way that we have adopted personalised medicine we should start planning for personalised food.

Agronomy, as well as human health, could be revolutionised by a better understanding of the microbiome, both on land and in the ocean. Our understanding and application of a healthy earth and ocean microbiome will allow us to reseed the ground or restock the ocean with beneficial bacteria, which could protect plants from drought or fish from diseases while making them more nutritious and tasty as well as correct years of intensive monoculture farming and climate change.

With regard to pathogen detection, Mars and IBM have launched an experiment that may revolutionise food safety. They are trying to define the presence of pathogens by monitoring microbiome evolution. Each food sample of a given raw material contains a vast community of living bacteria and viruses that either originated with the primary production or entered at some point along the food processing chain. The researchers are using genetic sequencing to determine the identity and relative quantities of each microbial species.

The theory is that safe batches of a given food all have a fairly standard set of microbes. A shift in the microbiome, then, could signify that something is amiss – a pathogen has spiked, a toxin is present or the item labelled 'beef' is actually from another animal altogether. By routinely sampling the microbiome of food, researchers could pinpoint and stop safety issues before the food leads to sickness. Much like the human microbiome, understanding the normal microbiome of food will become an essential cataloguing exercise.

Food microbiome is also seen as a way to enable traceability and transparency, as food products all have microbiome footprints that show where they were grown or shipped. Experiments on garments show it is possible to tell within 100 kilometres where the material originated based on its environmental microbiome. The same is likely true with food. This highlights again the need to reference all existing microbiomes on the planet, as initiated by groups such as the ones involved in the Earth Microbiome project, the Human Microbiome project, American Gut project or, most recently, the Global Foodomic project.

The food industry is also looking at the possibility of creating plastic remediation microbiomes. This can be done by using new microbiome-inspired biofilm in order to protect the product with a highly biodegradable packaging to replace plastic. As this is still a long way off, research is currently working on a specific microbial mix that could help speed up the degradation of plastics and decrease their environmental impact.

When applied to food production, a microbiome could also be used as a type of bio-protection against pests. If we can increase the right mix of bacteria in soil, we can make plants more resilient to pests and grow more and better produce. Specific mixes of bacteria could replace pesticides, hormones, GMOs and antibiotics. The idea is to mimic what happens naturally when the right balance of microbes is present.

The world is only waking up to the microbiome complexity and must develop academic and industrial partnerships, experience new projects, find new applications and train new talents. Ultimately, proper monitoring of the microbiome could enable the mapping, detection, prevention and remediation of any food safety issue in tomorrow's world.

Research is currently working on a microbial mix that could help speed up the degradation of plastics and decrease their environmental impact.

Stable isotope and trace element (SITE) 'fingerprinting' for food authenticity

The globalisation of food markets and the relative ease with which food commodities are transported through and between countries and continents means that consumers are increasingly concerned about the origin of the foods they eat. There is growing enthusiasm among consumers for high-quality food with a clear regional identity. The reasons for this vary and include:

- patriotism
- specific culinary qualities or purported health benefits associated with regional products
- a decreased confidence in the quality and safety of foods produced outside their local region or country
- concern about animal welfare, food miles and 'environmentally-friendly' production methods.

Recognising food origin is also important for LMICs. It is a way of rewarding national production efforts and giving recognition from external markets. Geographical indications (GIs) (labels used on products that have a specific geographical origin and possess qualities or a reputation that are due to that origin[50]) are a form of marketing that can be used for both the promotion and protection of regional food products. A GI defines the production method or origin of a product where a given quality, reputation or other characteristic of the food can be credited to its geographic origin. The benefits of GI include: quality assurance (reputation), fair competition, protection of the brand name in the retail market (domestic or international), price premium, linking valuable products to rural areas, reconnecting consumers and producers, and protecting traditions.

The FAO and the European Bank for Reconstruction and Development have identified, 'the promotion of linkages between local producers, their local areas and their food products through geographical indications as a recognised pathway to nutritious food systems and sustainable development for rural communities throughout the world'[51]. The EU is starting to recognise formally GI foods produced in countries outside the EU through its protected geographical indication and protected denomination of origin legislation, for example, Chinese products including Longjing tea, Jinxiang garlic, Yancheng lobster and Zhenjiang vinegar.

Production of tea in Longjing village.

Unfortunately, the added-value attached to foods with GIs can also lead to fraudulent substitutions with inferior products. This, in turn, can lead to unintended food safety issues, reputational damage, the contribution of barriers to international trade and, ultimately, poverty. An EU recommendation calls for newly registered GIs to use procedures that verify the origin or essential qualities of the product. Arguably, the most promising analytical methods for GI verification include stable isotope and trace element (SITE) profiling or 'fingerprinting'.

Stable isotope technology looks at the molecules in products, including food products, and works out what elements they contain (for example hydrogen, oxygen and different types of carbon). This technology then compares these elements to an existing database of food products to say whether the product is genuine or fake. The elements act as a unique fingerprint showing, for example, other substances that have been added[52].

In order to apply this technology, it is necessary to gather information about the natural SITE fingerprint in the area or region from which the product originates over a number of growth cycles or harvests. This information can then be added to a food authenticity database or library for comparison should food fraud products be suspected.

The lack of existing databases and libraries, and the limited connectedness between them, are key stumbling blocks for using SITE fingerprinting to test food authenticity. Over the years, efforts to establish global databases have faced major challenges related to data sharing and intellectual property. To make SITE fingerprinting work, we need a compilation of global, independent, trusted, reference datasets against which countries can easily compare suspected fraudulent foods.

Technologies and trends to shape a new food safety system:

New technologies in data science

This section continues the exploration of the development of a new food safety system by looking at how new technologies in data science can be employed to meet the limitations of the current food supply chain.

New technologies in data science can be employed to meet the limitations of the current food supply chain

Gathering data to help traceability

Big data and predictive analytics

Big data in food safety is difficult to compile and compare, with a multitude of collection methods and data formats across supply chains, compounded by corporate security and confidentiality concerns. Companies in the food industry face an overwhelming amount of data related to raw material and ingredient sourcing, product processing and packaging, supply chain operations, markets, sales and food safety systems. This ultimately contributes to large datasets often linked through internet-based systems. At the same time, tools and techniques that can be successfully put in practice are lacking, for example, tools that mine data and complete meaningful analyses to contribute to greater operations efficiency.

Big data management systems can aggregate and analyse immense volumes of data through complex algorithms to enable predictive analytics, target hidden costs and anticipate the risks or critical events before they happen. This process provides information on traceability, transparency and an improved level of safety for the product. Using existing data and the proven algorithms, it is possible to define a model that will estimate when and where the next issue – whether it be food safety, social or environmental – is likely to happen and how to address it in advance.

This process is currently used by large brands and authorities to prevent food crises and recalls and has proven to be efficient. Approaches such as distributed ledger technologies, blockchain and digital ecosystems (which are described later in this foresight review on page 62), represent a far better way to monitor sourcing and production of food in the supply chain in order to achieve real-time supplier compliance. Big data can also be used more broadly in food production to understand, for example, the ecology of soil, the movement of pathogens through an ecosystem, supply chain integrity, product traceability and heavy metal contamination of food, soil and water. A sample taken from a drain can help reveal, for example, the cause of a listeria outbreak.

Looking to the future, challenges to the application of big data in food safety include structured versus unstructured data, how to capture data and where to store it and how to collect data consistently in multiple formats with confidentiality and safeguards in place. When it comes to consumption, big data is also a source of controversy. While there is clearly a benefit to monitoring people's food – including their intake – in order to better tackle diseases such as diabetes and obesity, ethical issues remain since this data could potentially be used by companies (insurers, for example) when people do not abide by intake recommendations.

Industry 4.0: connected factories, the internet of things and real-time compliance

Industry 4.0, also known as the industrial internet of things (IIoT), incorporates technology to create a completely connected industry. It collects information about processes, equipment performance, supplies and orders, and then aggregates big data to generate information from suppliers, manufacturers and customers.

Collecting customers' data is easier now than ever. Tracking people's preferences has been streamlined through online shopping with websites keeping information to make it easier for a customer to repeat orders. Predicting customer desires can increase profits by catering to exactly what people will buy, when they will buy it and how much they will buy.

Industry 4.0 turns manufacturers into predictors for operations and equipment maintenance. A US brewer, for example, has integrated smart manufacturing onto its factory floor in order to predict when its equipment will need maintenance, which has reduced downtime by 50% and increased production without raising costs[53].

Wireless sensors throughout a factory collect data about performance and downtime of equipment and can determine when a piece of equipment needs replacing before it breaks down. For example, vibrating screens need constant monitoring for strength and tension, which sensors can do automatically. Predictive maintenance helps food manufacturers keep grains and other bulk foods flowing through the processing plant, prevent blockages and reduce downtime.

Despite its advantages, a recent survey showed that only 48% of manufacturers felt ready to transition to Industry 4.0[54]. Several barriers stand in the way of them fully embracing the IIoT in their facilities including information overload, a recurrent issue when a manufacturer automates or digitises the factory to solve human-based problems. Also, just like any other technology, smart manufacturing comes with hidden costs. Not only does it need an up-front investment, it also needs constant maintenance and higher-skilled (and, therefore, higher-paid) employees to operate a sophisticated system.

Regardless, many companies recognise the overwhelming amount of operational records that are being routinely collected and the opportunity to find operational cost-savings by mining this wealth of information through advanced data analytics and investing in the people trained to do so. In addition, food audits have to move from a 'snapshot in time' and sampling exercise with an on-site auditor, who physically verifies limited records over a couple of days, to a fully connected real-time system encompassing the entire supply chain and any online device operating in the supply chain.

Any deviation or error will be automatically identified and corrective action advised or immediately taken. Over time, the entire system will be able to learn from any issues that have occurred and always apply the right correction, which will be enhanced over time. This machine and systemic learning is clearly a first step towards AI.

Obviously, the right expertise will be needed at some point to gain the greatest possible advantage. Monitoring will be done remotely online with automated corrective responses. Onsite actions will be limited to cases where real risks are anticipated, and action will be focused on addressing these risks. Industry 4.0 should eventually help manufacturers meet the demands of the coming decades and become predictive instead of reactive, enabling a preventative, risk-based approach to food safety and food fraud.

Remote sensing, assessments, satellites and drones

New technologies offer new ways to monitor the flow and compliance of food products in the supply chain. Satellites, drones, cold chain or remote sensing equipment, once consolidated, could be used to create a new model to verify that supply chains meet the level of compliance expected in different areas.

There is still a lot of development needed, but some early attempts look promising. For example, certain large companies are now using satellite data to monitor the real sustainability of palm oil production. Through heat maps and other technologies, images can be used to assess yields, evaluate manufacturing sites, define the presence of growers, alert on wildlife intrusion and define the date and quantity of harvested production, matching it with records in the supply chain.

Satellites and other earth observation approaches have a significant role to play. There have been step-wise changes in the value and application of satellite data for traditional uses such as land management, precision agriculture, crop yield prediction, forest loss and supply chain management (for example infrastructure, sea transportation). The advances in satellite observation resolution, spectroscopy, frequency of coverage (for example PLANET) and video (for example Earth-i) are being combined with platforms for communicating information. Such technological advances (for example Ecometrica) offer a wide range of opportunities

to combine knowledge acquired through Earth observation with other information, and address and report on many development indicators including those related to food safety and security[55].

Technologies like satellites begin by creating an electronic field record (EFR) as the single source of 'truth' for each farm. Similar to the electronic media, the EFR is populated with premium, exclusive data such as:

- soil data such as moisture at multiple depths, nutrient content, fertility and type
- equipment data gathered from IIoT sensors in devices such as seed drills and sprayers
- farm practice and workflow data gathered from cooperative growers such as planting and harvesting dates, fertiliser and pesticide application rates and harvest outputs
- weather data
- high-definition visual imagery from multiple satellites, drones and planes.

Using satellites, it is possible to identify crop coverage and health. By combining this information with other data from the decision platform, yield can be forecasted. Next, drones can be used to collect images of the fields. They use traditional image recognition to identify pests or crop diseases. It then becomes possible to move from a fragmented and obscure food supply chain to a fully transparent and integrated one, enabled by new technologies.

As for remote audits, drones or webcams can be used for long periods of time in dangerous and complicated environments such as war zones and offshore. Image recognition has become quite mainstream. It is no longer necessary to employ data scientists who understand neural networks in order to use this technology.

IBM has developed an AI-enabled scanner, for example, that uses AI models to recognise the specific characteristics of an object, to detect signs that are invisible to the human eye and to verify an object's authenticity. The technology can distinguish, for example, different types of oils and wines, or inks and labels. The scanner is a portable analytics solution that can identify unique liquids and substances and is composed of two parts:

- an optical device that captures details of the substance, for example, its hue, saturation, value, viscosity and micron-level attributes; it can also identify the presence of specific DNA sequences; this device can be attached to a mobile phone
- analytics libraries that recognise authentic liquids and substances from counterfeit copies.

The scanner can capture detailed information, place the record on a blockchain and, when the physical substance is bought or traded, the person who buys it can scan the substance with their device.

Storing and showing the flow of data: Blockchain (distributed ledger technologies)

We have recently witnessed a steady increase in the number of announcements on the use of blockchain to enhance food traceability and its ability to track a product's journey. These include reports by food retailers (Walmart, Albert Heijn, Carrefour), food manufacturers (Nestlé, Unilever, Driscoll's), traders (Bunge, Cargill, Louis Dreyfus and ADM on grains) and even NGOs (Oxfam with rice from Cambodia).

Blockchain has the potential to change the way people buy and sell food, interact with government and verify the authenticity of everything from property titles to organic vegetables providing a fixed and trusted record of food distribution. It combines the openness of the internet with the security of cryptography to give a faster, safer way to verify key information and establish trust. Blockchain – a new way of recording transactions – is clearly part of the solution for improving food traceability and, therefore, also food safety. As such, it meets a key demand from increasingly informed customers who know what they want to eat and want to be sure about food authenticity.

More importantly, blockchain holds potential for a new type of governance that is more open and decentralised for food supply chain business models. This concept is key when it comes to critical goods such as food; data ownership by the very large players at the end of the supply chain is becoming a controversial issue.

Blockchain is one tool in the many options available for supply chain management and traceability, offering critical functions related to:

- management of smart contracts
- a distributed ledger, that is to say, 'a consensus of replicated, shared and synchronised digital data geographically spread across multiple sites, countries or institutions.'[56] There is no central administrator or centralised data storage.
- the security of cryptography.

While conceptually not a new technology it offers a useful option for companies to consider. There are, however, some concerns being raised over the hype and use of blockchain as a 'silver bullet' solution for food authenticity, food fraud and food safety solutions.

A blockchain is decentralised, free, secure and available to those linked to a blockchain, and could be opened up to other users, possibly the public. No single user can control a blockchain and the data does not belong to anyone but is accessible to everyone in the system. In this sense, it provides an agnostic platform that is a key element for such a sensitive topic like ensuring safe and sustainable food supply chains.

Until now, hopes for a fully open platform have not been achieved for food. All existing use cases are permissioned ledgers owned by IBM or other private entities (for example Food Trust Blockchain powered by IBM and joined by Nestlé, Walmart, Dole, Carrefour, Kroger).

Blockchain has been known mainly for cryptocurrencies such as Bitcoin and for holding records for financial transactions. However, its application to the assurance sector could be an efficient way to track the transaction of smart contracts, certificates, transitions and events, to track products and consignments with ease throughout complex food supply chains.

The food system struggles to identify and remove food that has been recalled. When a customer becomes ill, it can take days to identify the product, shipment and vendor. Some blockchain proofs of concept have shown they are able to obtain crucial and timely data from a single barcode or receipt, including suppliers' details on how and where food was grown and who inspected it. The database includes information from the pallet to the individual package.

Walmart recently reported a comparative case study using a blockchain to trace back a package of mangos to the source in 2.2 seconds instead of the usual seven days[57]. Walmart and IBM worked with suppliers to capture key information at each point in the food system. Similar initiatives are taking place all around the world. Driscoll's conducted a trial on products delivered to Walmart stores to gain a complete set of data on the farm, warehouse

and stores where it was sold. This trial was more successful than previous efforts, which broke down at the retail level. Now it plans to take this level of product identification back to the individual harvester level. If successful, these trials could change how all other food retailers and manufacturers monitor food and take more efficient action when something goes wrong, spurring big leaps in food safety, cutting costs and saving lives.

Blockchain does not, however, offer a failproof solution. A significant problem remains. Unlike document-based financial or assurance transactions, food has physical attributes making it perishable and subject to substitution, dilution and other forms of fraud. The link between physical asset and digital records is complicated requiring reliable forensics to assure authenticity and limit fraud. Initial records can be corrupted and the only way to stop someone from falsely registering a food item is to have another trustworthy system or management procedure prevention mechanism in place besides an encrypted, distributed ledger. The food industry has such certification and management systems in place through years of partnership with certification bodies, auditors and suppliers.

The reliance on barcode or radio-frequency identification (RFID) does not really provide assurance and integrity for complex products (raw materials, animal, grains, etc.) in the supply chain. Regardless, blockchain is an enabling innovation, which, together with other technologies, will change the current model of agro-food supply chain risk management.

There is, for example, a potential link among genome sequencing for blockchain to capture DNA or environmental microbiome fingerprints of a given product to evolve into the next generation barcode of a particular food product. This will make traceback and product-specific verification easier.

Blockchain is not a solution to traceability but rather a way to make the data available to a network of users and stakeholders, as long as the traceability data is valid, verifiable and uncorrupted. The distributed ledger process could still play a significant role in improving transparency and, more than anything, help people start to think about the trustworthiness of the data that goes into the block.

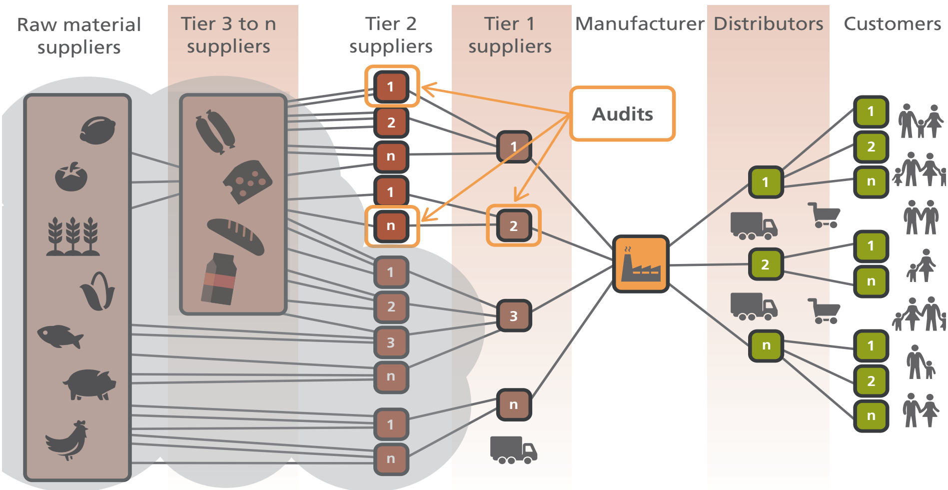


Figure 8: Current food supply chain: Not connected and low transparency

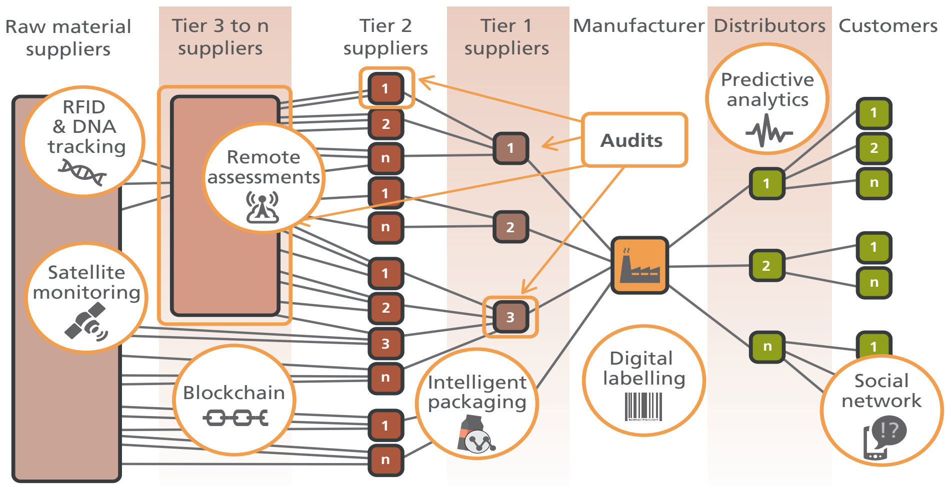


Figure 9: A new connected ecosystem with traceability enabled by new technologies

Technologies and trends to shape a new food safety system: Social evolutions

In addition to new technologies in life science and data science, social trends are helping to drive a new food safety system. Consumers are driving a change by demanding food that is not just safe but also sustainable and produced in ways that align with their own ethics.

Consumers are driving a change by demanding food that is not just safe but also sustainable and produced in ways that align with their own ethics

Food as a new identity

A new generation of consumers is driving a food revolution. These trend setters have a new set of values. Millennials are approaching food in a different way. Food makes them what they are – as it does all of us – but they are prepared to pay a premium to get the food they want. They want food that is healthy but, importantly, they also want food that is sustainable and free from modern slavery, GMOs and animal abuse.

Forty-seven percent of the younger generation eat more healthily[58], while 30% are willing to pay a premium for healthier food. Convenience, discount and e-commerce stores are growing three times faster than hypermarkets[59]. Generation Z influences 77% of family spending on food[60].

In a number of countries there is also an emerging consumer-driven demand for minimally processed food products, which are rich in nutrients, such as vitamins, and sensory qualities, such as aroma, taste and texture. To meet this demand, the food industry is looking to replace classic processing techniques, such as sterilisation, with alternative, novel techniques including non-thermal processing (cold pasteurisation, ultrasound, electric pulse fields, high hydrostatic pressure and plasma).

Furthermore, the industry is looking to use fewer antibiotics and preservatives and replace them with natural antimicrobial compounds. Although the above alternative approaches are promising, the way they act on the food microbiome remains largely unknown, which limits their general adoption by the food industry. A systematic understanding of these and any associated risks is necessary for their widespread use by the food industry as well as to support consumer confidence.

Chasing traceability

Traceability is a growing concern for consumers around the world. So far, traceability is limited due to a high, but fragmented, number of international stakeholders involved in the food supply chain as well as to a high number of tiers in any given food production process. All in all, it is complicated for end consumers to really know where their products come from and how they have been produced.

In addition, labelling information is increasingly difficult to understand using various acronyms, codes or different terminologies for the same components. Fructose, for example, may not be included under sugar. All of this contributes to consumers' anxiety around food.

Following the Wikipedia and OpenStreetMap (the free wiki world map) examples, open food databases driven by citizens are currently gaining increasing momentum and are a big issue for food brands. The largest one, Open Food Facts based in France, has a European reach, gathering nutritional and other labelling data for over one million products from 50,000 contributors all over Europe. It makes this information available for free to over 100 different applications used daily by over seven million consumers while shopping. The various applications use different levels of interpretation to help people understand the content and quality of their food. YUKA – a free and independent mobile application – allows users to scan food product labels to gain clear information on the health impact of the product.

The recent growth of consumer-driven databases that help decrypt labels is mostly based on Nutriscore (initially based on UK FSA Nutrition and adapted for all EU countries through an EU directive) as well as other open databases, schemes or standards. These initiatives are seen as a way to educate people, improve citizen science on food and reward brands' or retailers' efforts to produce good food.

In the US, initiatives such as the American Gut human food project or the Global Foodomics project are other examples of citizen science that give better understanding and control to a group of consumers who want to be well-informed about what is truly in their food and in their body.

New ways of life

Vegan, vegetarian or organic consumption is growing fast and now represents more of an ideology or a lifestyle than just a diet. The main drivers are health, environment and animal welfare. These new developments create new types of food production but also new types of risks and pathogens.

Consumers expect convenience throughout the stages of the supply chain with which they interact. Purchasing channels have expanded to include online shopping and food delivery companies; both sectors grow in value year on year. Demand for convenience also affects food formulation and packaging as consumers seek to eat on-the-go from flexible, re-sealable packaging incorporating convenient features.

Technologies and trends to shape a new food safety system:
Summary - Tomorrow's food systems

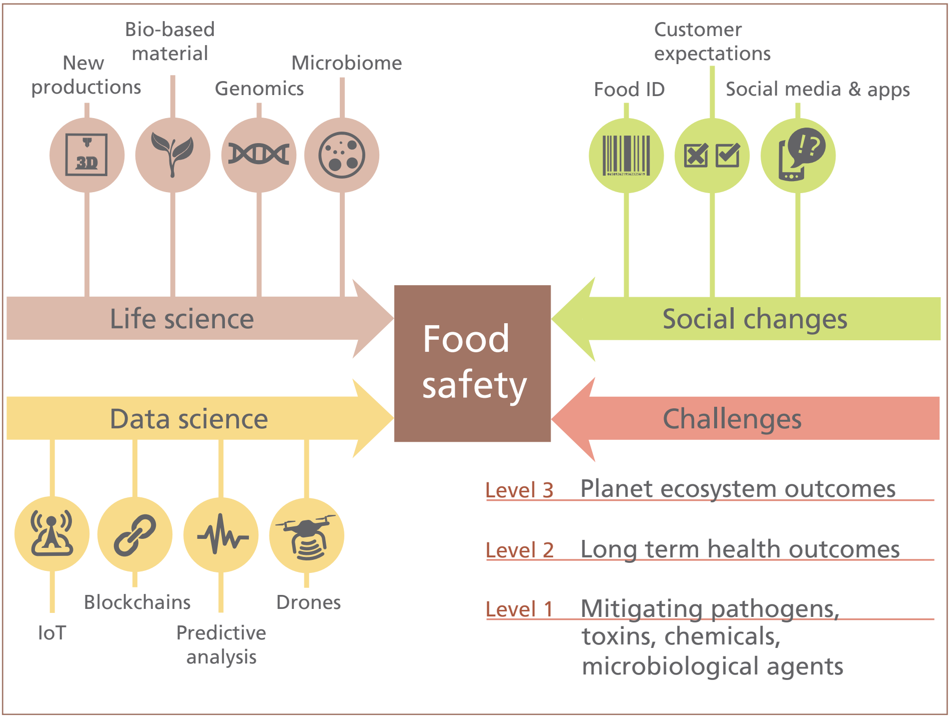


Figure 10: Tomorrow's food systems: factors driving change

Life sciences, data science, and social changes will have a powerful influence on the way our food systems will evolve in the future, and the way we manage the safety of these systems and the safety of the food delivered through these ever-changing systems. Food safety is a complex challenge and the diagram also shows three levels of challenges, at different timescales, for a holistic understanding of food safety. Level 1 is ensuring that pathogens, toxins and other harmful contaminants are not in our food. Level 2 shows us that we must consider the longer term health effects of our foods, for example malnutrition through long term deficiencies or through excess resulting in obesity. Level 3 shows that we must also put the long term health of our planet at the centre of any changes we make to improve food safety. Our planetary ecosystem needs to be able to support safe food for all.

Findings and recommendations

Food safety is a truly global subject with the potential to impact every human being. Although it is a relatively new subject for Lloyd's Register Foundation, food safety connects many of its areas of focus. The findings of this foresight review have significant cross-over with other foresight reviews such as distributed ledgers for engineered systems, resilience engineering, public understanding of risk and ocean engineering.

Drawing from the content of this foresight review and the historic experience and credentials of Lloyd's Register Group (LR) in the food industry, this review recommends that the Foundation should focus on the following three areas to make the greatest possible contribution to traceable, safe and sustainable food for everyone.

Education and training

This topic is pivotal to all of the recommendations. By bringing research into the public arena through education, it is possible to impact consumer awareness of key food safety issues and encourage, for example, healthier eating decisions based on scientific facts, not assumptions. By delivering professional training in the food supply chain we can improve food safety and traceability.

It is critical that knowledge about nutrition, food safety and sustainability continue to be deepened and broadened through education and training. Action is needed through coalitions and partnerships that work together locally and globally.

This could be applied to:

- Developed countries by reaching people through education, bringing knowledge around all aspects of food safety to new innovations in nutrition, food security and sustainability. The social benefits of this would be significant and could be developed through partnerships using social media, open platforms, authorities, academia and exhibitions.
- LMICs are the countries most impacted by food diseases. A holistic approach is essential. Governments, NGOs, universities – everyone must work together. Local education programmes aimed at the general public should go hand in hand with increased awareness programmes in local governments. Food safety must be incorporated into educational programmes in schools and universities to ensure lasting improvement. The current lack of food safety specialists is a critical problem in LMICs and prevents action to limit risk using local skills. For example, auditing bodies are almost unable to operate in these countries due to the lack of food safety competences, while the food industry struggles to find local people familiar with food safety best practices in order to work in their facilities. This recommendation should obviously align internationally with UN agencies such as the FAO and WHO.

Traceability to enable a safer food supply chain

Traceability is critical in the food supply chain in order to increase safety of food products. It helps to provide the required level of transparency to clients and improve the discoverability of the root causes of problems that lead to food scandals. It also helps to identify and reward those who make efforts to minimise environmental, social and food safety risks in their production processes. Traceability supports sustainable economic growth, poverty reduction, food security and environmental protection, promoting food safety, and animal and plant health.

The food supply chain is complex and fragmented, which greatly limits traceability. Yet new life science and data science innovations offer real opportunities to address this challenge and deliver noticeable improvements.

It is recommended that the Foundation's focus should be on challenges that relate to the connection between physical food stuffs and digital records – so-called 'phygital' solutions. This includes new markers for food such as stabilised isotopes, microbiomes, DNA, genomics, smart packaging and satellite monitoring, as well as better mapping for food stakeholders, remote and real-time monitoring of the supply chain, open platforms and online auditing.

Technologies that can help shorten the distance or duration of the food supply chain can also help improve traceability and safety: when you know where food comes from, you worry less about safety. Also, less food transportation is ultimately more sustainable.

One of the side effects of traceability will be the inevitable need to reveal changes that must be made in the supply chain. Farmers, many of whom live in poor and vulnerable rural communities, will need to implement these changes. Education and research will help them limit unsafe practices and adapt to the transparent food supply chains of tomorrow.

We need to connect the steps in food supply chains to make them more traceable and more understandable and, therefore, ultimately safer for consumers. The public already drives the change it wants to see, creating, for example, food fact apps that give greater clarity and readability into the precise content of food, like salts and sugars, but also the precise origin too. Each time they eat or drink, consumers are voting for the food system they believe in and the world they want to see, but they cannot 'vote' if they do not understand what is in their food and where it comes from. They demand greater clarity on food information and labelling, and this has consequences for traceability in the supply chain. We must develop new technologies to meet this consumer demand for traceability and safe food supply chains.

Ocean of food

Aquaculture is the fastest-growing food-producing sector in the world and could meet the global population's increasing demands for food but it is one with which too few business and government leaders are familiar. The first requirement is to improve current practices in aquaculture which, like any new industry, encounters severe inefficiencies and safety issues for both operators and production.

Also, given the low current use of offshore areas, the potential of aquaculture is obvious. However, there are many challenges to developing more offshore aquaculture. These are challenges we must seek to overcome:

- Higher levels of investments relative to traditional aquaculture infrastructure
- Increased risks due to operation in exposed conditions
- A lack of knowledge about the farmed species (behaviour and welfare) in rough environments
- Too few efforts to harness complex soil and marine microbial communities (microbiomes) for the sustainable production of food
- A lack of understanding of the consequences for the eco-system.

Organisations are starting to look at solutions that would help overcome these issues. Momentum is growing and various ocean food pilot projects now exist. In Panama, 12 kilometres off the Caribbean coast, cobia fish are being reared in submersible cages with the aim of producing 5,000 tonnes of fish per year by 2020.

The Foundation should support work in offshore aquaculture in combination with other activities in a multi-use setting or standalone environment. There are major challenges to overcome, but the need to safely produce safe food, and reduce the impact of aquaculture on coastal areas, more than justifies these efforts.

LR's history in the maritime business and its recent development in energy and food safety make this challenge a logical one for the Foundation to support. This focus remains consistent with previous Foundation commitments to Technical Standards for Safe Production of Food and Feed from marine plants and Safe Use of Ocean Space (SOMOS), led by Wageningen University.

Appendix A: Definitions

Food safety

Food safety is the absence, or safe acceptable levels, of hazards in food that may harm the health of consumers. Foodborne hazards can be microbiological, chemical or physical in nature and are often invisible to the plain eye; bacteria, viruses or pesticide residues are some examples[61].

Food security

Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life. Household food security is the application of this concept to the family level, with individuals within households as the focus of concern[62].

Nutrition

Nutrition is the intake of food considered in relation to the body's dietary needs. Good nutrition – an adequate, well balanced diet – combined with regular physical activity is a cornerstone of good health. Poor nutrition can lead to reduced immunity, increased susceptibility to disease, impaired physical and mental development, and reduced productivity[63].

Food sustainability

A sustainable food system is usually defined as collaborative network that integrates several components in order to enhance a community's environmental, economic and social well-being. It is built on protecting the diversity of both plants and animals and the welfare of farmed and wild species over the entire planet. It has to be a global effort.

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