The 9th CS3

Chemistry for Sustainable Food: Challenges and Perspectives

CS3

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ORGANIZATIONS

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China
The Chinese Chemical Society (CCS)
The National Science Foundation of China (NSFC)

Germany
The German Chemical Society (GDCh)
The German Research Foundation (DFG)

U. K.
The Royal Society of Chemistry (RSC)
The UK Engineering and Physical Sciences Research Council (EPSRC)

U. S. A.
The American Chemical Society (ACS)

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The Chemical Society of Japan (CSJ)
The Japan Science and Technology Agency (JST)

White Paper Production

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Table of Contents

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Chemistry for Sustainable Food: Challenges and Perspectives

Held every two years, the Chemical Sciences and Society Summit (CS3) gathers some of the foremost chemists from around the world and challenges them to propose meaningful approaches to address the most pressing issues facing society in the areas of health, food, energy, and the environment. Most importantly, as its name implies, the CS3 has arisen from the global chemical sciences community, with a self-imposed challenge: identify what and how the chemical sciences should actively commit to these imminent issues. Differing from conventional international meetings, the CS3 is uniquely designed in that the participants from each member country represent both a leading chemical society and a relevant funding agency. The event is conducted in a highly constructive format, and is rotated on each occasion among the participating countries. Each CS3 issues a white paper that summarizes the discussion and presents viable and implementable solutions to the general public and governments around the globe.

The CS3 initiative is a collaboration between the Chinese Chemical Society (CCS), the German Chemical Society (GDCh), the Chemical Society of Japan (CSJ), the Royal Society of Chemistry (RSC) and the American Chemical Society (ACS). The symposia are supported by the National Science Foundation of China (NSFC), the German Research Foundation (DFG), the Japan Science and Technology Agency (JST) [previously by the Japan Society for the Promotion of Science (JSPS)], and the UK Engineering and Physical Sciences Research Council (EPSRC).

Entitled “Chemistry for Sustainable Food: Challenges and Perspectives”, the ninth CS3 focused on global food instability and was jointly hosted by the Japanese members, CSJ and JST, with Professor Kazuhiro Chiba, President of Tokyo University of Agriculture and Technology, as Meeting Chair; local funding by JST; and meeting logistics managed by CSJ.

The in-person meeting took place on September 19–21, 2023, at the CSJ Headquarters in Tokyo, to explore the role of chemistry in delivering food security and sustainability. Scientists representing the participating societies and agencies worked together to identify and clarify the roles chemistry plays in food production, and to address meaningful ways in which the chemical sciences can contribute to building a more secure, sustainable global food system.

The 2023 CS3 "*Chemistry for Sustainable Food: Challenges and Perspectives*" was aimed at defining and proposing the missions of the world chemical science community, including chemical societies and funding agencies, for sustainable food, which is definitely among the most serious, eminent, and challenging issues in the world, perhaps rivalling energy security and climate changes: We humans could survive without abundant energy but we could not without sufficient food; according to the UNESCO, currently over 800 million people are on the brink of starvation.

Focusing on the roles of chemical sciences and technology, in particular, the 9th CS3 consisted of three sessions:

Session 1: ***Chemistry for Revolutionary Food Engineering***
Robust and Resistant Crops
Engineered Livestock and Seafood
Synthetic Food

Session 2: ***Chemistry for Sustainable Food Production***
Food Factory and Smart Agriculture
Novel Food-Processing
Alternative New Food

Session 3: ***Circular and Sustainable Chemistry for Food Sustainability***
Circular Chemistry for Nitrogen and Phosphorous
Chemistry for Water Sustainability
Environmentally Friendly Agrochemicals
Food Packaging, Monitoring, and Recycling

Several countries have initiated major discussions on the role(s) of chemistry for food sustainability, and some have started research and development projects to deepen the discussion by proposing the above-mentioned issues. In 2023, for example, the American Chemical Society published a special issue entitled "More Food, Less Chemicals" [*Chem. & Eng. News* **2023**, *101*, 28 ff (#15, May 8)]. It argues for the development and spread of food production technologies with less environmental impact, moving away from conventional food production methods that rely on the functions of chemical pesticides and fertilizers. In Japan, the Moonshot R&D project led by the Cabinet Office started in 2020, and the fifth of its nine goals is "Creation of an industry that enables sustainable global food supply". The technological basis of the project significantly involves chemistry and chemical sciences, directed to, for example, a reduction in the use of chemical pesticides and fertilizers and to the development of innovative technologies for processing, preservation, packaging, and transportation, so as to achieve a significant reduction in food losses, among many others.

As emphasized in this CS3, the importance of the role of chemistry in addressing food sustainability must be recognized once again: Food is truly an accumulation of chemical compounds, and it is essential to view food as a substance from the perspective of its production through biological and biochemical processes until it reaches the human palate. In these processes, various substances move through the soil, rivers, oceans, atmosphere, biosphere, etc., undergoing chemical changes. To comprehensively understand these processes and a sustainable food supply from a chemistry viewpoint is an ultimate, unavoidable challenge to pioneer the next era.

This White Paper summarises the discussion and the proposals formulated in the summit, hopefully to provide convincing arguments directed to not only the chemical science community but global governments, industry, and the general public.

The above mural depicting agricultural workers was painted by Carl Morris in 1942 and installed in the United States Post Office in Eugene, Oregon.

Executive Summary

Food production has increased dramatically since the beginning of recorded history. The expansion of agriculture has been a result of not only increased cultivation, but also increased understanding of agriculture and the development of technology, from the wheel through to artificial intelligence. Early advances resulted from macroscale observation and experimentation. Irrigation, crop rotation, incorporating manure and other organic by-products as soil enhancers, and selective breeding were relatively early technological achievements. In the twentieth century, mineral-based soil enhancers, synthetic pesticides and herbicides, and mechanisation became incorporated into agricultural practices to the point of becoming indispensable. These advances have not occurred without economic environmental and social costs. Fossil-sourced energy requirements have become exceedingly high, and ecological disruption has become increasingly widespread. In many important agricultural regions, irrigation has become dependent on subterranean aquifers, which are being exploited at an unsustainable rate, and if they collapse will not be recoverable. Climate change is creating less predictable weather and seasonal changes, as well as impacting the availability and quality of fresh water.

Demand for higher agricultural production has been driven by the increase in human population. This increase has accelerated significantly over the past century, with a four-fold increase in population since the 1940s. These two trends of human population rise and demand for food are inextricably linked. According to the United Nations, the world population (8 billion in 2023) is projected to increase by about 20% by 2050 and an additional 10% by 2100. An often-posed question is “How can this growing population be fed?” however, a perhaps more rational question is “Will this growth continue without productivity improvements in agriculture?” Human population growth predictions are dependent on the availability of food. Although food production has to date increased in line with demand, system limits are being approached, planetary boundaries have reached a tipping point and some possibly already exceeded. And despite steadily increasing food production, hunger, malnutrition, and food insecurity have remained stubbornly persistent. In the current era, hunger and malnutrition are to a large degree related to access to food and distribution issues; that is to say, they are socioeconomic and geopolitical issues. Yet chemistry and technology can contribute to improving food security in many ways. Whether a challenge is addressed by frontier technology or by traditional practices, gaining greater understanding of the food system on a chemical basis can provide important guidelines and options for approaching food security.

Food systems-related research is extensive and ongoing in academia, industry, and government. The range of academic and policy fields is broad and ranges from narrowly focused pure research to large scale applied development. New processes and novel foods that more efficiently use water, energy, and other resources as well as present a smaller environmental footprint are being conceptualised and developed. In addition to increasing food supply stability and sustainability, improving nutrient profile and providing novel food that will appeal to consumer taste are high priorities. Developing circular or regenerative rather than linear production systems that cycle by-products back into the production stream where the materials are biotransformed by microbes (including fungi), or other organisms is a very promising research area. Utilisation of by-product streams as feed stocks has long been employed and development and nuancing of this practice is ongoing. Highly specific gene editing has facilitated remarkable expansion of understanding of chemical biology and subsequently contributed to agricultural technology. Exploring microbiomes in soil and water, studying their interactions and developing new analytic techniques to probe these complex natural systems are areas of great importance. And critically, systems thinking is becoming an important element in research and development and ensuring that innovations are socially acceptable and inclusive offering opportunities for all global communities. A number of recommendations have arisen from this summit. These recommendations aim to provide nutritious food for all, healthier sustainable eating, new and connected supply chains, food security and sustainability, and reduced waste in the food system. It is highly stressed, in the report, that food production must be viewed as dynamic, complex and at times vulnerable and the presented recommendations in this report should be viewed as interacting elements within a cyclical food system. Soil health is a critical element to agriculture, and continuing research into soil microbiomes and symbiotic interactions between plants and other soil organisms should be strongly supported. Biological and mineral processes in soil play important roles in the nitrogen and phosphorus cycles, as well as the carbon cycle, and greater understanding of these processes is highly relevant to addressing climate change. The connection between soil health and human health is strong. Nutrient loss through food loss and food waste needs to be urgently considered. Research addressing food loss, such as improving preservation and packaging should be encouraged, as well as continued development of approaches to utilising by-products and food waste as resources (see for example https://www.bbc.co.uk/news/business-67548961) or commodities. Efforts toward greater understanding of human nutrition and ways of improving nutrient profiles should be strongly encouraged. The role and degree of animal agriculture in nutritious and affordable diets should be considered from an objective, systems level view considering nutrition, how and where livestock is raised, and the multiple roles played by animals in the food system. Objective, systems level analysis of other, non-animal food sources and emergent novel sources is necessary as well. Public perception of chemistry, technology, and agriculture should not be disregarded. Improved communication and expansion of systems thinking in education are vital. And perhaps most importantly, growers, processors, and consumers must be involved in the deliberations on the future focus of the food system.

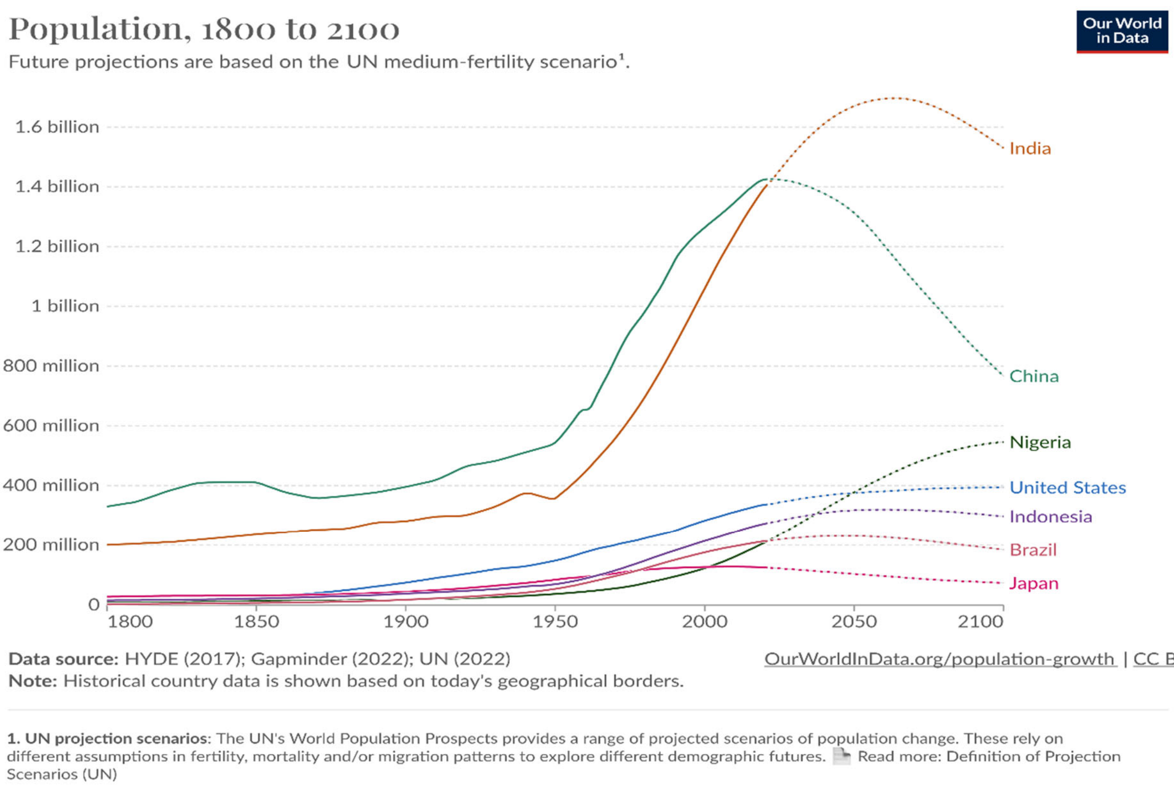
Introduction

“Earth provides enough to satisfy every man’s needs, but not every man’s greed.”-

—Mahatma Gandhi

Food is a primary need. We may need warm clothing in cold weather and we may need medical care when we are ill, but our lives unambiguously depend on a steady supply of healthy and nutritious food from conception to death. We humans arose as communal hunter-gatherers, and as such we thrived. Yet it was the development of stationary agriculture that made the formation of villages, towns, cities, and great civilisations possible, and indeed, it was stationary agriculture that initiated the genesis of human civilisation. The efficient, reliable production, storage, and processing of food facilitated the division of labour, allowing civilisation to flourish. As understanding of agriculture grew, production increased, and with it, human population. Practices such as irrigation, crop rotation, and selective breeding were followed by mechanisation, industrially produced fertilisers, and chemical pesticides and medicines and vaccines for livestock. Improvements in processing and preservation led to greater shelf life and safety, improving food security. These combined developments have allowed the human population to increase to over 8 billion people, a four-fold increase over the last 80 years.

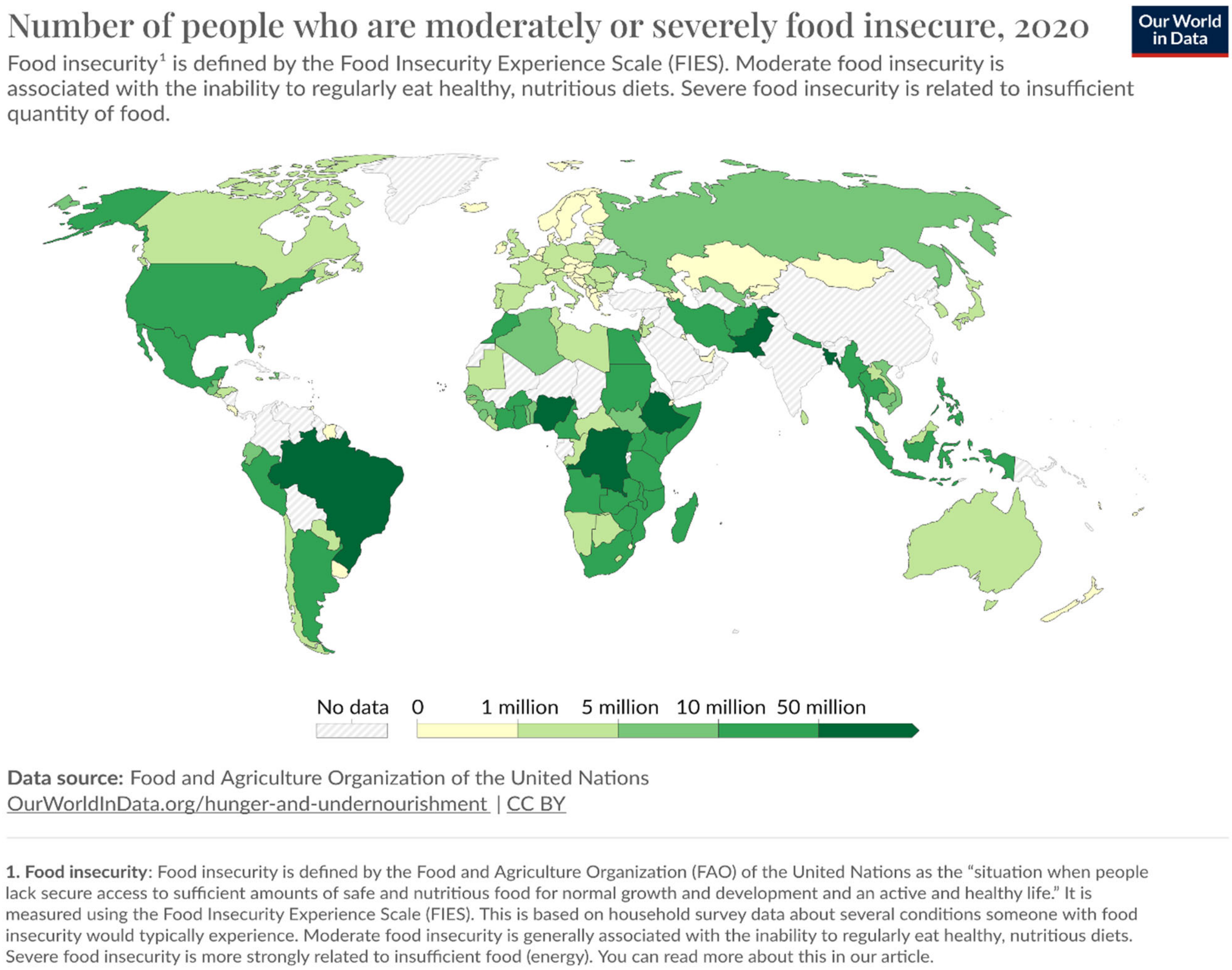
Despite the steady advance of human agriculture and increased food production, hunger remains stubbornly persistent. According to a UN FAO report, about 9% of the global population was undernourished in 2022, while at the same time obesity was equally prevalent. It is reported that between 691 and 783 million people globally faced hunger in 2022, and this level of chronic undernourishment is expected to continue through the decade. Furthermore, an estimated 22.3 percent of children under five years old were stunted, 6.8 percent wasted, and 5.6 percent overweight globally in 2022. Affordability is reported to be a critical factor in determining nutritional status and food security. Food security is critically important for achieving the first three Sustainable Development Goals (SDGs) outlined by the United Nations in 2015: no poverty, zero hunger, and good health and well-being. The Sustainable Development Goals Report 2023 reveals the persistent nature of hunger. According to this report, more than 600 million people globally are expected to face hunger in 2030, largely due to affordability relative to



incomes. It is also estimated that 1 in 3 people worldwide experience moderate to severe food insecurity. Furthermore, it is revealed that malnutrition persists worldwide.

Viewed on a global scale, food security at present is largely an issue of distribution, that is to say, it is largely an issue of logistics and economics. However, environmental constraints are becoming increasingly apparent. Numerous agricultural regions currently rely heavily on subterranean aquifers that are being rapidly depleted and once collapsed, will be unrecoverable. Precipitation is becoming less predictable, which results in less predictable crop yields. And increasing aggregate atmospheric temperatures are disrupting agricultural production as well. Furthermore, the environmental impact of large-scale industrial farming is becoming increasingly a cause for concern.

On September 19-22, 2023, the 9th Chemical Sciences and Society Summit was held in Tokyo, Japan, and attended by leading scientists representing chemical societies from Japan, China, Germany, the United Kingdom, and the United States of America. The theme was Chemistry for Sustainable Food: Challenges and Perspective. The content was divided into the following sub-topics: 1. Chemistry for Revolutionary Food Engineering, 2. Chemistry for Sustainable Food Production, and 3. Circular and Sustainable Chemistry for Food Sustainability. The goal of this summit was to present current research related to food and food production, and to discuss ways in which the chemical sciences can contribute to addressing food security, hunger, and nutrition.



Chemistry for Revolutionary Food Engineering

Scientific investigation related to agriculture, food processing, and nutrition is extensive in academia, industry, and the public sector. The scale of research activities ranges from molecular level investigations on a laboratory workbench to industrial scale engineering projects and from the study of symbiotic interactions between roots and microbes to exploration of entire supply chains from farm to fork. The range of topics is too broad to cover here, but a few of the research areas presented at the 9th Chemical Sciences and Society Summit are briefly introduced below.

Food Processing

Novel Potato Processing

China leads global potato production with almost 100 million tonnes grown annually. To address storage challenges, Chinese researchers have developed a dry, rice-like form of potatoes, offering a cheaper, nutritious alternative. The process is energy and water-efficient, with optimised waste management. Potato starch production, totalling 6 million tonnes annually, generates substantial by-products which if not utilised can end up as waste. Research on utilising these by-products includes, extracting protein from potato juice, repurposing solids as animal feed, and using wastewater for irrigation.

Whole Bean Tofu

Traditional tofu production creates soybean curd residue, which currently is either discarded or fed to livestock, causing environmental issues and nutrient loss. An alternative process discussed reduces residues, boosts yield, and produces 500 grams of tofu from the same raw material that yields 350 grams traditionally. The resulting tofu is more nutritious while maintaining traditional characteristics that consumers look for.

Fungal fermentation

Many by-products of food production are either not digestible by or are unpalatable to humans, and are either used as livestock (animal) feed, or are simply discarded as waste. One approach to novel utilisation of agricultural by-products is application of fungi. Unlike animals or plants, fungi are able to digest lignin. Palm husks are a major by-product of palm oil production, and currently are burned as waste, having a significant environmental impact. Recent studies in Germany have shown that palm husks can be used as a substrate for fungi. The fungal material produced is not directly useful as food for humans or livestock, but is suitable for black soldier fly larvae. The resulting larvae or adult flies can then be used as a nutrient source for feed for poultry or in aquaculture.

Aquaculture

Shrimp is a major source of protein and cultured shrimp dominates the market. This is particularly true in South Asia. The quality and yield are highly dependent on water salinity and alkalinity, as well as feed source. Microbiota also play a significant role. System-scale understanding on a molecular level and improved metabolite analysis in aquaculture can help improve efficiency and sustainability. This applies generally across aquaculture irrespective of species. This approach can be applied to other agricultural systems too.

Sustainable Breeding

Genetic modification is a topic that attracts considerable attention, however, exploiting genetic variation in crops and livestock by humans is as old as stationary agriculture itself. Humans have for millennia chosen organisms with desired characteristics and through selective breeding producing modified organisms. Sweet oranges, Cornish game hens, Fuji apples, and Haas avocados all arose through a combination of favourable mutations using traditional breeding practices to give desirable traits. In the twentieth century, genetic modification was first directly induced through exposure to ionizing radiation or chemical modification giving random, uncontrolled mutations. As the understanding of chemical biology and genetics increased, more controlled and selective approaches could be used and organism modification was accomplished by gene integration using recombinant DNA technologies. Improvements in the precision of gene editing were accomplished around the turn of the 20th century with the advent of CRISPR CAS9-assisted gene-editing, which helps facilitate precise targeting and recognition of nucleic acid base pairs, often producing single mutations identical to mutations that could arise through natural processes. (CRISPR: Clustered Regularly Interspaced Short Palindromic Repeats; CAS9: CRISPR Associated Nuclease No 9) Genetic modification, whether through traditional selective breeding or through target directed genome editing, has great potential to provide food crops with characteristics such as improved resistance to insects and disease, increased heat and drought tolerance, increased yield, improved nutritional profiles, and longer shelf-life. Public perception, however, must be considered and effective communication and inclusive, deliberative processes are essential.

Chemistry for Sustainable Food Production

Chemistry has played a vital role in food production since the very beginning of human agriculture, although it has not been the explicit subject of policy until relatively recently. Any life form or process can be described in chemical terms and thus, growing a plant, cultivating a fungus, or raising an animal can be considered as facilitating a chemical process. Observing that seeds placed in soil at a certain time and under certain conditions result in a sprouting plant is chemistry in action. Reflecting that cabbage, when shredded, salted, and placed in a sealed container gives sauerkraut or kimchi is an example of a chemical reaction, even if we are unaware of the exact chemical and microbiological details of the process. Crop rotation to improve yield, selective breeding of plants and animals to increase desirable traits, malting grain to give sweetness, fermenting sugar to ethanol, distilling spirits to concentrate ethanol, and making yoghurt to improve storability and nutrition all can be understood as chemistry. Thus, humans have been making chemical discoveries in food and agriculture and applying this knowledge, for thousands of years. Although unaware of the detailed processes on a microbiological or molecular level until the last few centuries, on a macro scale our understanding of how we can produce food has been rather remarkable.

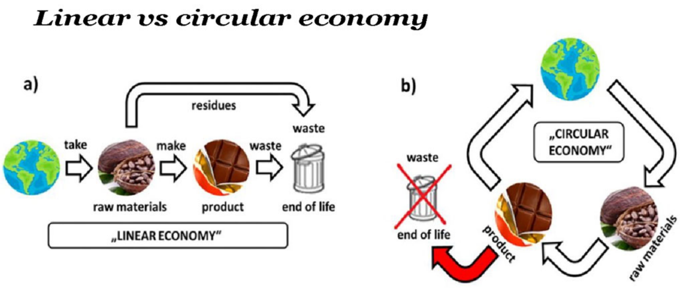
The preparation of kimchi is an example of chemistry in food production that came about without awareness of the underlying processes. Image from Wikimedia Commons.

Unfortunately, humans have often failed to understand the unintentional impacts of agricultural practices in a systems context. We rather often view the field or the pasture as an isolated unit without considering its place in the entire landscape. This is not surprising; immediate results focus attention and carry behavioural weight. When human populations were relatively small, the impact of clearing land for food production, contemporary issues such as the effect of agricultural runoff (diffuse pollution), the effect of fertilizer application, biological or mineral, and the impact of animal agriculture fell within the capacity of the surrounding environment to maintain environmental and ecological balance. Agricultural practices and the surrounding environmental systems had the capacity to co-evolve in a dynamic equilibrium. Indeed, entire species, such as maize and domestic fowl evolved with human agriculture, as did local ecosystems that were surrounding farms and farming communities. As human populations grew, however, the impact of agriculture also increased, often dramatically. In the last two centuries, countless species have been decimated or become extinct because humans either destroyed their habitat or did not see them as economically or culturally important. The environmental impact of mineral fertiliser and synthetic pesticides has also been substantial. Reliable, high crop yields have been achieved, greatly improving food security and human welfare, yet at the same time, excessive or incorrect use of agrochemicals has often resulted in negative impacts on the environment as well as human health. (see for example https://www.europol.europa.eu/media-press/newsroom/news/2-040-tonnes-of-illegal-pesticides-seized-and-21-suspects-arrested-in-global-operation) This has also been the case with the use of veterinary (and human) pharmaceuticals with concerns over residues in foods, antimicrobial resistance and contamination of river systems. Thus, the great contribution of scientific approaches to agriculture should be acknowledged, but at the same time, learning from past unintended consequences and embedding system-wide thinking as we go forward are vital.

Circular and Sustainable Chemistry for Food Sustainability

Transition to a more Circular Economy

The global economy is dominated by linear economic thinking. A linear economic system requires a continuous stream of input to deliver the required outputs and assumes limitless resources and limitless room for continued growth and expansion. The associated markets focus on the outputs that the market is prepared to pay for with the consequence that negative externalities such as deforestation, water pollution, or greenhouse gas emissions are not accounted for in the economic model. Dominated by short-term thinking, this can result in inefficient use of resources and excessive production of waste. Circular economic thinking, however, considers interactions at micro-, meso-, and macro levels, and results in more effective use and reuse of resources, minimising impact, but potentially limiting growth potential. Transition to a more circular economy will be critical if worsening environmental and geopolitical instability is to be avoided.



J. Braybrook. Presented at the 9th CS3.[*1]

Food Waste and Food Loss

The definition of food waste and food loss varies somewhat depending on the defining organisation, institution, or agency, but broadly speaking, food loss occurs along the production chain while food waste occurs at the retail and post-retail stage. According to the UN FAO, 14 percent of food is lost prior to retail, while an additional 17 percent is lost at retail and consumer levels. Some of this loss is avoidable, such as spoilage due to insufficient packaging or storage. Much of this is unavoidable, that is to say, a portion of the food may be unpalatable or indigestible to humans, for example, citrus peels or walnut shells (see earlier section). The highest priority should be given to maintaining the viability for edible food to remain as a source of human food. (see related; https://www.food.gov.uk/research/behaviour-and-perception/the-creation-of-food-waste)

Technical and structural improvements, such as improved storage, processing and packaging, and using cultivars more resistant to spoilage would reduce food loss. Understanding signaling pathways involved in ripening has already led to significant advances in food preservation. For example, sensors for ethylene (ethene) and catalysts for ethylene (ethene) scavenging have enhanced the degree of control over fruit ripening. Discarded food can of course be composted, but more effective utilisation of the nutritional content or chemical complexity would be desirable and is often possible. Food by-products unsuitable for humans have long been utilised as feed for livestock, and this can be further developed. Agricultural by-products and unused food can be a rich source of value-added chemicals as well. Colours, waxes, oils, sugars, and flavonoids can be extracted from numerous agricultural by-products using biorefining techniques. Waste that is unsuitable for human or animal consumption can also be used to generate fuel.

Compostable waste bin. Image from Wikimedia Commons.

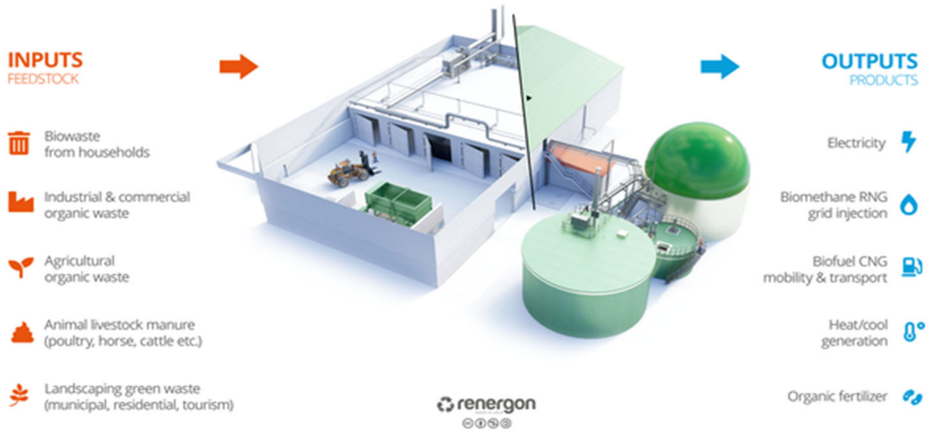
Utilisation of Unavoidable Food Waste

Primary and secondary processing of food yields significant amounts of unavoidable food waste estimated at 30-35% by weight. If allowed to decay then the material contributes to greenhouse emissions but also is a loss of valuable nutritional resource. Unavoidable food waste e.g. the parts of plants that cannot be digested by humans or animals, can be considered as Nature's periodic table of structure, form and function, as it is rich in an array of chemicals and materials that can be utilised. For example, global orange production is about 70 million tonnes annually, and of this about 30 million tonnes goes into juice. The rest, the residue, is rich in cellulose, hemicellulose, pectin, flavonoids and terpenes. For example, limonene is an important commodity terpene for use in flavours and fragrances as well as a useful chiral building block for fine chemical synthesis.

Pectin is a useful commodity, rheology modifier or thickening agent used in many food applications beyond just making jam. Industrially, pectin is extracted using heat and hydrochloric acid which generates significant volumes of aqueous acidic waste. Recent studies in the United Kingdom have demonstrated an acid-free microwave process relying on the natural acidity of the citrus residue and operating at lower temperatures for the production of pectin in addition to extraction of essential oils, antioxidants and defibrillated celluloses within the context of a zero-waste biorefinery. These approaches should be applicable to treatment of other unavoidable food waste streams, such as pits, seeds, peels, and rinds.

Waste to Energy Conversion

Food waste can be converted to usable energy in a number of ways. It can be directly converted to heat through traditional biomass burning typically used for cooking and heating purposes. Advanced technologies can convert food waste to more conveniently used biofuels through pyrolysis by heating under anaerobic conditions. This process can be used to provide solid fuel (biochar), similar to charcoal, liquid fuel (bio-oil), similar to heavy petroleum, or syngas (biogas), which can be used to prepare liquid hydrocarbon fuels or chemical feedstocks on an industrial scale via Fischer-Tropsch chemistry. Biomass can also be converted directly to usable thermal energy by high temperature gasification. Anaerobic decomposition by microorganisms can convert biomass to (bio)methane, which then can be used as a fuel or as a chemical feedstock. This can also be applied to manure. Carbohydrates can be converted to bioethanol and biobutanol through fermentation, and lipids can be converted to biodiesel and related fuels. These technologies are also well developed on a commercial scale.



Biogas plant. Image from Wikimedia Commons.

Packaging

Food packaging plays a vital role in reducing food loss and food waste, yet it also presents a number of environmental problems. Food contact packaging must also be in compliance with food contact materials legislation to prevent chemical migration into the food. Reusable packaging can be effective, efficient, and have a minimal environmental impact if food is consumed locally, but can present a significant logistics and energy burden if transported long distances. Durable packaging may not be biodegradable, and modern containers often use composite materials and laminants that are difficult to recycle. Pollution from discarded food packaging has become a major environmental problem, and nanoplastics and microplastics have become ubiquitous in the environment. Biodegradable packaging, however, may not provide sufficient preservation protection for the contents, and may incur other environmental burdens resulting from the manufacturing requirements and raw material sourcing. (see related (https://www.food.gov.uk/research/behaviour-and-perception/the-creation-of-food-waste)) Ideally, to minimise environmental impact food packaging would be edible or at least easily compostable. Edible films and coatings for food are one example of where chemistry is being applied to deliver effective solutions.

Inclusion of antioxidants and other preservatives has been long established in food packaging. Butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) have been effective antioxidants in food and packaging for many decades. As an alternative, biologically based, degradable antioxidants, preservatives, and disinfectants can potentially be developed. Additionally, active and intelligent packaging systems can utilise sensors that monitor biochemical reactions and visually indicate the freshness or safety status of the contents. Intelligent packaging solutions using sensors could allow real-time evaluation of food quality without the need for special equipment or processes and would reduce reliance on static rather than agile duration date coding. Chemistry and packaging technology can contribute greatly to both creating novel packaging materials and improving traditional packaging systems to reduce food and packaging waste.

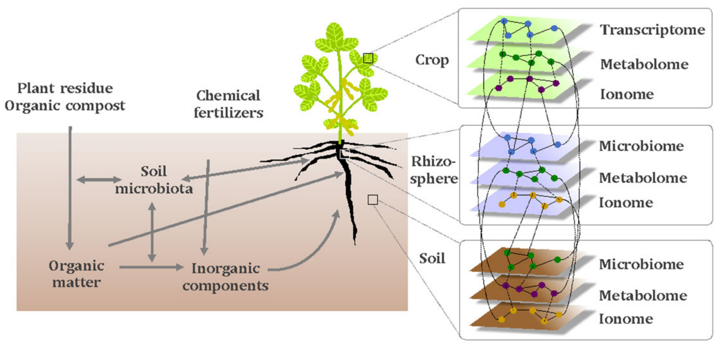
Soil and Soil Health

Soil is a mixture of inorganic and organic solids, liquids, and gases, and is a major component of the terrestrial ecosystem. Soil is a major reservoir in the carbon, nitrogen, and phosphorus cycles and soil health is critical for healthy agriculture. Advances in botany, entomology, microbiology, and chemistry have greatly improved understanding of soil ecology and subsequently improved understanding of agronomy, yet many aspects of soil health and function remain to be discovered. This is particularly true for our understanding of soil microbiomes. The relationship between plants and soil microbes is being actively studied on many levels. Investigation on the organism level as well as soil analysis based on metabolites, influence of pH, and biological profile is also progressing. The microbiome plays important roles in carbon dioxide, nitrous oxide, and methane generation, a concern in terms of the global warming potential (GWP) of greenhouse gases as well as in the carbon, nitrogen, and phosphorus cycles. Greater understanding of soil ecology could lead to more efficient, sustainable fertilisers and soil enhancers as well as reduced greenhouse gas emissions from soil and plant activity and improved nitrogen use efficiency, carbon sequestration and mineralization. Improved utilisation and reduced leaching of inorganic nitrogen and phosphorus is highly desirable.

Multiomics analysis allows a shift from study of a single interaction between one plant and one microbe to integrated study of interconnections between a plant and a microbial community in a natural environment.

Planetary boundaries and capacity limits of the carbon, nitrogen, and phosphorus cycles must be recognised, and the effect of

Multi-omics Analysis of Agroecosystems

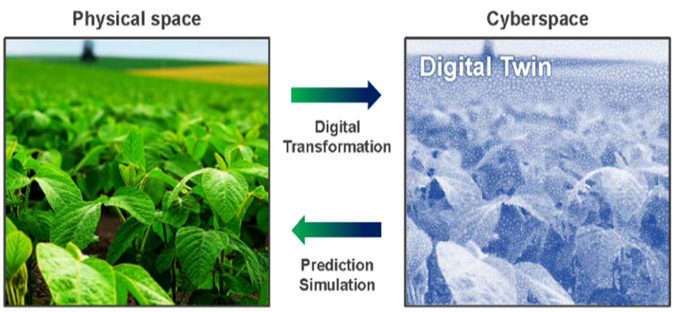


Y. Ichihashi. Presented at the 9th CS3.

human activity on these systems more thoroughly understood. The environmental effect of industrial scale use of these natural elements, in agriculture and more widely, both extracting them as resources and discharging them after use has not been trivial. The same could be said for the efficacy of use of fresh water resources. Furthermore, application of synthetic chemicals in agriculture has also impacted the environment. Historical use of chemical pesticides and herbicides like DDT and 2,4-D have also led to non-trivial consequences and understandable public distrust. Urban and industrial pollution has also impacted on the environment and is a source of concern in agricultural areas especially where they lead to degradation of soils. These chemicals include 'forever chemicals' such as PFAS, heavy metals and pharmaceutical products in sewage, dioxins and polyaromatic hydrocarbons among others. At the same time, it must be recognised that the contributions of chemistry to agriculture have greatly increased productivity and improved global food security.

Chemical use in itself is not bad if appropriate governance, controls and surveillance systems are in place, but excessive modification of the environment occurring through chemical use is problematic. The adoption and practice of green and sustainable chemistry within the context of planetary boundaries and SDGs is paramount. Farming and food production and promotion of certain practices should be based on scientific knowledge and be evidence based. The underlying chemistry, both naturally derived, and as a result of human intervention, requires the integration of knowledge of animal science, environmental science and plant science with soil science in order to construct a robust, enduring food system. Understanding the non-target impacts of agriculture, whether it is land use, water use, or the use of chemicals is vital for maintaining robust, reliable and resilient production systems and avoiding undesirable side-effects. Combining modern scientific understanding with traditional practices, such as crop rotation and nutrient cycling back into the soil is a promising strategy. Multiomics approaches to gain greater understanding of the microbiome, root systems, and soil chemistry are being explored. Computational models are being developed but, due to the significant complexities involved, whilst digital twins are being developed there is still no complete agricultural model in cyberspace.

Digital Twin in Agriculture

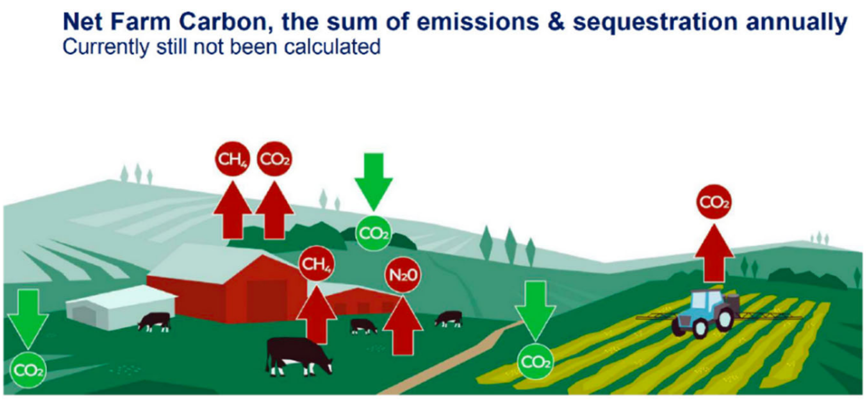


Y. Ichihashi. Presented at the 9th CS3.

Landscape View

A healthy, resilient food system must meet the nutritional needs of human society and be environmentally compatible. In the current era, achieving a healthy, resilient food system faces numerous challenges. Climate change, in general, is making weather patterns more severe and less predictable, resulting in less reliable growing seasons and harvests. In addition to climate change, farming in many important agricultural centres relies on subterranean aquifers for irrigation which are being irreversibly depleted. Even if climate change is not considered, as human population continues to rise and demand for fresh water increases, water availability is becoming an increasingly critical problem. Expanding irrigation systems and desalination projects could provide some relief, but these have associated environmental impacts and energy requirements as well. Competing demands means that availability of land for agricultural use is also an issue. Thus, a landscape system level view is essential. Maximising short-term food production output i.e. depleting water and other resources today and ignoring the impact for tomorrow is detrimental to sustainability. Clearing wild spaces for food production, and expanding irrigation of cropped land or intervening in natural water systems can increase near-term food supply, but can disrupt ecological systems leading to undesired consequences such as biodiversity loss and destruction of carbon sinks. Furthermore, social, economic, and political demands must also be taken into account.

Considerations of animal agriculture well illustrate the relevance of systems thinking in the food system. In pre-industrial agriculture, as well as in hunter-gatherer societies, animals, with respect to the food system, function as bioconverters. That is to say, herbivores, in particular ruminants, consume food that is either inedible or not efficiently utilised by humans, and convert it to food suitable for humans in the form of meat, milk, or eggs depending on the species. In extensive agriculture, this is fairly efficient; the animals forage on land unsuitable for the production of human-edible plants. However, there is concern over ruminant production of methane and its global warming potential. Methane is a by-product of fermentation by the rumen microbiota. There is much global research on-going to mitigate methane production and effectively determine other pathways to address hydrogen utilisation produced by microbial fermentation in the rumen. In intensive industrial-scale animal production, animals are often fed grain and legumes that could otherwise be eaten directly by humans, and the feed conversion rate varies significantly between species. The concern over the carbon intensity of animal derived food products means that many argue a diet completely free of animal products would be highly desirable. Yet total abstinence is also problematic. Animal derived foods such as eggs, milk and meat are nutrient dense and contain a range of essential amino acids, minerals, and vitamins. Additionally, humans require dietary cobalamin (vitamin B12), which they can only acquire from animal-based foods or synthetic supplements. Thus, making appropriate changes to food production practices can be very challenging in the face of so many competing interests. Changes that benefit consumers may not benefit distributors, changes that benefit small producers may not benefit large producers and their shareholders, and changes that ease environmental burden may lead to problems



N. Scollan. Presented at the 9th CS3.

accessing a nutrient rich diet. While chemistry can contribute to greater understanding of these issues and provide approaches to address them, they should be considered from both scientific, political, and socio-economic perspectives.

Public Perception and Overall Trends

According to an FAO report, agriculture and related use emissions accounted for 17 percent of global greenhouse gas emissions from all sectors in 2018. The impact of agriculture on the environment is significant in other ways as well. Natural water systems are impacted by irrigation, agrochemicals, and run-off. Biodiversity is being impacted by large scale monocultures, broad-spectrum pesticide use, and habitat destruction. At the same time, there is a pressing need to increase the quality, stability, and sustainability of food production. Current agribusiness models are argued to not be sustainable in the long term, nor is the current reliance on the agrochemical and agro pharmaceutical sector as drivers to deliver more sustainable practices include reducing chemical inputs and utilising a range of technological applications to deliver targeted chemical product use. Whether agricultural practices are changed in a revolutionary, disruptive manner or in an evolutionary, incremental manner remains an open question, but they will change, they have to. Adoption of green and sustainable chemistry practices can contribute greatly to our collective understanding and determining how we address the challenges facing the food system. The solutions need to have consensus as social, political, and economic factors are involved as well, e.g. how this will affect food affordability, or whether consumers will want to willingly change their food habits making public perception and engagement an important consideration.

The causes of food insecurity are not globally uniform, nor are the social and political factors that must be addressed in order to improve nutritional security. Each region, each state, each economic system, each culture faces related yet unique social, economic and environmental challenges. Yet at the same time, the size of the human population on the planet requires global governance coordination as well. Conditions and events in one region may strongly affect other regions, directly or indirectly. One global commonality is the necessity to engage with farmers, processors, retailers, shareholders, and consumers to welcome, or at least accept, the changes that are necessary to achieve sustainable approaches to food production, and to reach a consensus. We are not limited to a single path to success, but we must agree on a path or paths that we can all follow.

Perhaps the most important contribution chemistry as a science can make is clear, system level thinking based on empirical observation and experimental confirmation. Incorporating systems thinking into education could help move society in this direction. We need to develop an inclusive community that can embrace and address the complex challenges we collectively face. There is a much greater awareness of the interconnectedness of global food systems and this can be communicated more easily through our digital interconnectedness due to the rise of the internet. Increased awareness can be nurtured by supporting students early on to think on a system level and interdisciplinary scale. Organisations such as the American Chemical Society are strongly encouraging this and are actively developing programmes to incorporate systems thinking into undergraduate education and to connect curricula to environmental, industrial, economic, and social issues.

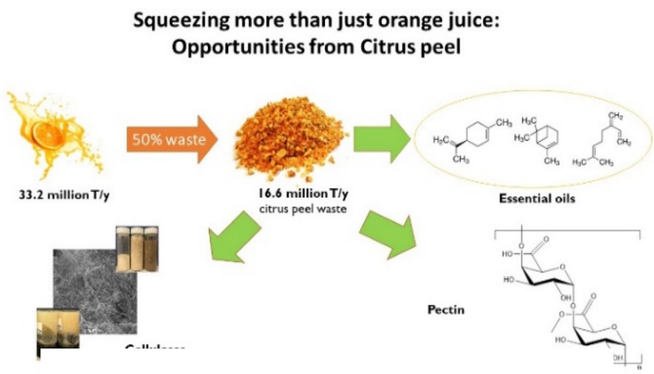
Recommendations

The challenge to solve the unavoidable food problem that humanity faces today and in the future from the viewpoint of "chemistry" is truly a challenge for the very survival of the human race. The current situation in the world is largely due to the dramatic expansion of the world population and human activities in tandem with the innovations in food production technology that began with the Green Revolution. Agriculture, as a food production activity, relies heavily on the regenerative power of the earth and nature, as well as utilizing the functions of nature. This balance has already been upset, and visible changes such as climate change are increasing the crisis at an unprecedented rate, as is the release of large amounts of carbon from the soil into the atmosphere and the loss of biodiversity. We now need to apply our wisdom to these issues and work together strongly to make them a common challenge for all humanity.

The current primary causes of food insecurity are related to logistics and distribution, and subsequently must be addressed as social, economic, and political issues. Changing weather patterns due to climate change will further exacerbate food insecurity. However, chemistry can contribute significantly to understanding food systems from a micro to macro scale, and provide a basis for improving production, processing, distribution, and nutrition, while at the same time providing a framework for achieving stability and sustainability. Although what is planted and how it is grown, how food is distributed, and what people eat are societal questions subject to human demands, human nutritional requirements, the conditions necessary for growing crops, and the scope and limitations of our biosphere are not. Chemistry can provide an array of potential solutions from which a sustainable pathway or pathways may be selected. Understanding on a chemical basis is critical for facilitating robust system assessments and to inhibit 'green washing' in order to provide a more robust and sustainable food system.

Extensive pasture and arable land with healthy soils are critical components of the agricultural system. Further investment in pure and applied research is strongly recommended. The soil microbiome provides abundant research opportunities across multiple fields, and could provide rich discoveries that would greatly benefit agriculture, and provide a reduction in greenhouse gas emissions and increased carbon sequestration. Greater understanding of the metabolite mediated symbiotic interactions between soil microbes, fungi, wild plants, and food crops could provide a basis for reliable harvests with a reduced environmental burden. The role of the microbiome in the nitrogen, phosphorus, and carbon cycles as well as the role of biologically mediated redox reactions in relation to carbon dioxide, methane, and nitrous oxide is a rich area of study. Understanding the role of soil in carbon sequestration and mineralisation has become increasingly important as atmospheric concentrations of carbon dioxide increase. Applied research toward sustainable fertilisers, pesticides, and herbicides is critical, and technology can play a role in being precise in their use and tracking their environmental fate.

Chemistry can contribute new processes to reduce supply chain food waste and food losses, enabling resource circularity for human re-nutrition. Chemistry can improve packaging to reduce food spoilage and increase shelf-life. Real time analytical methods can be developed to ensure food provenance, food quality and safety. By-products and unavoidable food waste have considerable potential for use as livestock feed, upgrading to processed food ingredients, feedstock for value-added chemicals, as well as composting and bioconversion. Extraction of oils, terpenes, alcohols, dyes, colours, waxes, sugars, flavonoids, and other components for production of commodity chemicals can be further expanded. Investigation of new extraction methods employing novel bio-derived solvents, ionic liquids, light, ultrasound, microwaves, and photocatalysis can be further supported. These areas could provide both social and economic benefits and merit strong public and corporate support.



Unavoidable Food Waste
A. Matharu Presented at the 9th CS3.

Growing food with high nutritional value and retaining nutrients throughout the processing and distribution chain all the way to the consumer is vital. Humans evolved as hunter-gatherers and thus have evolved to live on a mixed diet rich in macro and micronutrients. Understanding food production on a chemical basis can lead to harvests with greater nutritional value, and processing that not only preserves, but also enhances naturally occurring nutrient profiles. The importance of flavour and appearance should not be disregarded. Nutritious food is only valuable if consumers will actually eat it.

Creating a robust, resilient sustainable food system that meets the nutritional needs of society is critical, while at the same time, agricultural contributions to greenhouse gas emissions must be addressed and where needed mitigation and adaptation strategies must be put in place. Agricultural emissions of carbon dioxide, methane, and nitrous oxide are highly dependent on how and where a commodity is produced and processed, and it is important to understand how these emissions relate to the carbon cycle and to overall carbon footprints. This is particularly true for animal agriculture. Pasture raised livestock tends to have a more modest carbon footprint, whereas grain-fed feedlot raised cattle livestock tend to have a large carbon footprint, especially where the calculators include an adjustment for recent land use change. Significant reductions in consumption of animal products, particularly those intensively raised with a high feed conversion rate could provide significant reduction in greenhouse gas emissions as well as a reduced environmental footprint in general, particularly with respect to land and water use. A diet completely free of animal products, however, is not recommended without significant regard for supplementing nutrient deficiency for a number of important reasons. Animal products provide nutrients, including cobalamin (vitamin B12) that are not available from plants or fungi, that are necessary for human health. Furthermore, animals play an important role in efficient use of ecological niches such as pastoral regions that otherwise could not be utilised for food production. In traditional agriculture, livestock plays an important role as part of a complete cycle, and should be viewed this way in modern agriculture as well. Thus, the contentious issue of animal agriculture must be addressed as a question of how much is produced, where it is produced, how it is produced, and how it is consumed. These questions must be addressed for a number of plant-derived food products as well. The environmental and ecological burden of growing crops with high water requirement in deserts, use of fossil-fuel heated greenhouses to grow horticultural products in winter, and shipping tropical fruit to consumers across the globe must also be addressed. The trade-off between the environmental cost of transportation and that of local production should be carefully weighed as well as the benefits to less industrialised economies of food exports.

In this context, the development of innovative technology-based livestock and food production technologies that have a more modest carbon footprint will play an important role. Although pasture-based livestock production is expected to be useful, grass-fed cattle, for example, tend to produce high amounts of methane. Therefore, how to reduce methane production while raising grass-fed cattle will be an important R&D issue in the future. If methane emissions from the rumen can be reduced, the percentage of carbon converted to protein in meat and milk will increase, which will directly lead to increased profits for the livestock industry. Thus, a positive chemical perspective and technological development focusing on the carbon conversion process will play an important role. Cultured food production technology using algae is also expected to become important in the future. If such technology evolves, we can expect to use sunlight as an energy source, recycle nutrients-organic compounds and inorganic salts-without waste, and efficiently produce meat products in culture equipment. This is truly a challenge to a new concept of food production based on the philosophy of chemical conversion processes.

The public perception of science, engineering, technology, and more specifically chemistry must be addressed, ensuring greater public awareness and involvement in decisions. Mechanised agriculture, inorganic fertilisers, synthetic pesticides, and modified organisms have made modern agriculture possible, and without these developments, society would not exist in its current form. But with these advances have come pollution, environmental destruction, and many other unintended consequences. Public scepticism is understandable, and should be recognised. It is important for the public to understand what technology, and in particular chemistry, can provide, what it cannot provide, now and in the future and to the degree possible, to understand the world as a system, rather than just a set of unrelated binary decisions. Involving farmers, processors, retailers, and food service, and consumers is vital to achieving a robust, resilient sustainable food system. Corporate investment in food production has been and remains indispensable, yet ensuring that profit considerations do not obscure and take precedence over all other considerations is vitally important. Economic issues must be considered, but at the same time, economic systems should not be viewed as static and unchanging with time. Linear food supply chains highly reliant on inputs and with a number of negative externalities need to be reconfigured and redesigned to be more circular and more sustainable.

Communication and education are vital. Awareness must be raised throughout government programmes, consumer, producer, and non-governmental organisations, and both the public and private sector must be involved. International cooperation is essential, building capacity and capability where needed. Interdisciplinary communication should be increased, and interaction between business and academia should be nurtured. Furthermore, increasing emphasis should be incorporated into higher education of systems thinking. The food system affects all of humanity, and all of us have a stake in ensuring our food system is resilient, robust, and sustainable.

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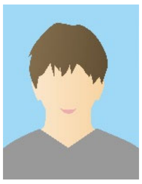

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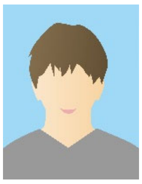

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GDCh GERMAN CHEMICAL SOCIETY

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