The vital ingredient

Chemical science and engineering for sustainable food

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RSC | Advancing the Chemical Sciences

IChemE
Institution of Chemical Engineers

Purpose of the report

The report is intended to provide guidance to funding bodies, policy makers, academics and industry on:

- the pivotal role that the chemical sciences and chemical engineering will play in the transformations that are needed to achieve a sustainable food supply;
- the priority areas for the chemical sciences that need support to advance fundamental knowledge development; and
- the importance of promoting closer links between food sector industries, universities and their students to ensure graduates have the appropriate skills mix to deliver sustainable food production solutions.

About the RSC

Since 1841, the RSC has been a leading society and professional body for chemical scientists, and is committed to ensuring that an enthusiastic, innovative and thriving scientific community is in place to face the future. The RSC has a global membership of over 44,000, with a further 300,000 associated chemical scientists internationally, and is actively involved in the spheres of education, qualifications and professional conduct. It runs conferences and meetings for chemical scientists, industrialists and policy makers, at both national and local level. It is a major publisher of scientific books and journals, the majority of which are held in the RSC Library and Information Centre. In all its work, the RSC aims to be objective and impartial, and is recognised throughout the world as an authoritative voice of the chemical sciences.

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About IChemE

IChemE (Institution of Chemical Engineers) is the hub for chemical, biochemical and process engineering professionals worldwide, with a global membership of some 28,000 members in over 120 countries. The Institution is at the heart of the process community, promoting competence and a commitment to best practice, advancing the discipline for the benefit of society, encouraging young people in science and engineering and supporting the professional development of its members.

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Key messages

The world faces a food crisis caused by climate change and competing land and energy demands, due to population growth and rising prosperity.

Chemical science and engineering will provide sustainable ways to match increasing demands for food with limited natural resources, enabling a reduction in environmental strain throughout the food supply chain.

Scientific literacy is required at the highest levels of the food industry and amongst food policy makers. This will be necessary for promising technical solutions to be recognised by those with the power to initiate change.

A skilled workforce must be supplied by forging closer links between food sector industries and universities. Graduates must be made aware of the breadth of opportunities available and possess the skills mix to deliver sustainable solutions.

Scientific leadership should come from the learned societies working together to provide common guidance, encouraging interdisciplinary research through facilitating dialogue, and promoting informed and balanced debate.

Government must recognise that limited natural resources and a profitable food industry are driving forces for investment in science and technology which will provide solutions for the sustainable production of nutritious food.

Regulations must be based on risk, accounting for both hazard and exposure. Substances cannot be banned on the basis of intrinsic hazard alone but on the likelihood that they will cause actual harm when used.

Industry must become more entrepreneurial to harness and develop new scientific technologies and operating procedures that will minimise waste and resource use whilst improving food quality, production and sustainability.

Table of contents

1 Executive summary

The world is facing a food crisis, relating to the sustainability of global food supply and its security. The strain on the food supply comes from climate change and the resultant competition for land use between food and biomass for energy, industrial and domestic use. This needs to be balanced against the need for wilderness areas to preserve biodiversity. Population and economic growth are major factors in the global increased demand for food. In addition they have caused a rise in demand for energy, which is still mostly derived from non-renewable sources.

The new affluence of emerging middle classes in India and China and their capability to purchase equivalent foods, challenges us to sustain adequate diets for all into the future. The peoples of the developing world deserve no less an opportunity for food and nutrition security than their counterparts in the developed nations.

The food supply chain in the developed world has arisen in recent times from the innovative use of petrochemical-based energy in agriculture, manufacture and distribution. The advances in chemistry and biology, and their large scale use, have kept food raw materials and ingredients in plentiful supply (and thus relatively cheap). This is unsustainable. The future worldwide challenge: to match energy and food demand with declining fossil fuel resources, without permanently damaging the environment, is the greatest technological challenge humanity faces. It will require all the skill and inventiveness we can muster, and the common recognition by all societies and individuals that the application of chemistry and its engineering is a key part of the solution.

The chemical sciences will be needed to ameliorate risks to supply, and to increase production efficiency in all stages of the food supply chain. The demands placed on the environment must be taken into account: use of land, sea and air; use of fresh water and energy; and the treatment of waste must be sustainable to secure a lasting supply of food. In the short term, supply may fall short of demand but in the longer term, global sustainability of food must come from the application of existing and advancing technology.

The scope of the report is global: it is focused on the UK and EU, primarily to inform UK and EU policy in a global context. The issues and future requirements for chemistry and its engineering in each link of the food chain are presented, from farm to landfill.

Primary agriculture

Climate change is predicted to have an adverse impact on primary agriculture and global food production. Thus, increasing productivity from existing agricultural land represents a significant opportunity. Historically, the increases in production of all major crops have come from higher yields as a consequence of improved varieties, better farming practices, and the application of new technologies such as agrochemicals and, more recently, agricultural biotechnology. Major opportunities exist for the chemical sciences in addressing sustainable crop production.

A consequence of global warming is a substantial alteration in the world's weather patterns, for example in the distribution of rainfall. A strong focus on developing and improving chemical engineering technologies to conserve and reuse water is required; including the optimisation of water use, treatment of contaminated water, recycling water, desalinating water and harvesting water for irrigation.

Modern biotechnology should be used to develop crops that are resistant to attack by pests and to environmental stresses, including drought and salinity. In addition, higher yields should be sought through enhanced responsiveness to fertilisers and pesticides. Nutritionally enhanced crops hold tremendous potential to provide significant benefits for human and livestock nutrition, health, welfare, and growth. Regulations in this contentious area must be based on an evaluation of the risk, using sound evidence, and not on a socio-political fear of new technology.

Research and development for improving the economics of using chemical and biochemical methods to extract cellulose from lignocellulosic fuel crops, such as switch grass, should be pursued as a priority to reduce competition for agricultural land.

Chemical sensing methods to measure diffuse pollution from agriculture should be promoted alongside remediation technologies. Research should be undertaken to improve understanding of the chemistry of recycling carbon and nitrogen in soil in order to help maintain sustainable agriculture and reduce emissions of nitrous oxide, a potent greenhouse gas.

In the absence of corrective action, the environmental impact of livestock production will worsen considerably. The use of chemical engineering to devise methods of treating supply chain waste to generate energy and biogas should be pursued. Disease in farmed animals should be tackled with research into the development of effective vaccines and veterinary medicines. Modern biotechnology should be harnessed to improve disease resistance, feed conversion and carcass composition.

The growth of aquaculture over the next two decades will involve intensification, improvements in productivity through breeding programmes, modifications of the cultivated organism and feed research to reduce the dependence on fish oil and meal. Water recirculation and aeration technology, coupled with the controlled use of antibiotics, can ease the stress caused by intensive farming but, unlike treating human or other animal diseases, few drugs are available for treating diseases in fish because of environmental concerns and a relative lack of knowledge about many fish diseases.

Food processing and manufacture

Continuity and security of supply of key raw materials for use in food processing and manufacture is a critical sustainability issue. Research should be undertaken into innovative sourcing of raw materials and alternative uses.

The application of novel enzyme chemistry and technology for use in ingredients, processing and preservation is a key area for development. This includes product structure and flavour release, taste and textural development and product changes at different stages of processing.

Processing areas identified for improvement include heat-transfer systems, low energy separation technologies, rapid heating and chilling technologies and fermentation technology. Innovation in engineering can increase operational efficiency, improve use of energy and the management of water and waste, and develop extraction technologies for the recovery and use of by- and co-products.

Nanotechnology also has potential contributions to make across the food supply chain.[1] These include non-contact sensors in food processing and packaging, new functional materials, food formulation and improvements in diet.

Hygiene and food safety can be improved by the application of analytical chemistry, surface chemistry and chemical engineering to improve hygiene through all stages of processing, including disinfectants, non-aqueous cleaning methods and the use of novel materials for handling food. In addition, authenticity, control and better management of products and ingredients through the food chain can be achieved by improvements to food analyses and diagnostics.

Distribution and retail

Retailers need to recognise and take advantage of their unique position to implement a successful approach to sustainability. The UK supermarket sector has a reputation for introducing innovation in the food sector and, by its size can and should champion sustainability in the UK and worldwide. For example, own brand products enable supermarkets to wield considerable influence over the entire supply chain. They can engage with primary agriculture, food processing and manufacture to ensure food safety and traceability, in addition to reducing waste in product and package.

Retailers need to ensure they commit sufficient resource and expertise to sustainability. This applies particularly to understanding of the various technologies involved that would not necessarily feature in traditional retailer-supplier technical relationships. For example, reductions in energy usage per unit of distribution centre and retail space will require state-of-the-art low-carbon technologies, renewable energy generation and energy-efficient practices.

Shorter supply chains through local sourcing, and adopting regional distribution centres (RDCs) as hubs for distribution can cut transport emissions considerably, provided the chain remains logistically efficient. However, the advantages of reducing mileage need to be balanced against possible increases in other emissions across the product lifecycle. Basing measures on food-miles alone ignores the impact of the supply chain as a whole.

A detailed and structured approach to the carbon footprint of a product over its lifecycle will provide a management tool for improvement, and a communication route to consumers relating to improved sustainable practices. The methodology for carbon mapping of products should be developed as part of a collaborative initiative between all sectors of the food chain and public bodies.

Consumer

The transfer of existing and new technologies to the developing world is of huge importance in order to achieve the necessary increase in food supply for these regions.

Difficulties arising in the developed world relate to excess production and consumption. Despite the increasing awareness of the consumer that diet and long-term health are related, obesity and its deleterious effects on health are increasing. The understanding and control of fat chemistry should be extended, further developed and promoted to bring about reductions in trans fatty acids (TFAs). Further research into the chemistry of fundamental food transformations should be undertaken with a view to creating products with a low glycaemic index (GI).

While macronutrients are generally well provided for in the diet of the developed world, formulation and manufacture of foods with an improved nutritional profile present many challenges to the chemical sciences, including better processing to maintain the presence of nutrients, or their addition and protection as ingredients, as well as their targeted delivery during consumption.

Research into nutrigenomics, to identify requirements for different demographic groups and tailored diets for individuals, should be supported, and the chemical sciences should be promoted to develop food that meets these requirements.

In the developed world, consumers want high quality, nutritious food at an affordable price in convenient packaging that does not have adverse effects on the environment. However they are increasingly bombarded with large amounts of often conflicting information, making it difficult to make balanced judgements in their purchasing behaviour. There is a need to explain the principles of product lifecycles to the public at large, and to explain in understandable terms, the technologies already embedded in the modern food chain as well as the benefits of new technologies.

A dialogue based on knowledge and an understanding of the social and cultural issues, together with a clear explanation to the public of the benefits as well as the risks of new technologies, is necessary between the public, government, regulators, media, NGOs and industrial representatives.

Supply chain waste

Waste arises at all stages of the food supply chain and technologies should be adopted to improve the efficiency of waste disposal through reduction and recycling.

The food industry can influence behaviour for the better, through product and packaging design, better integration of unit operations in production, and scheduling in manufacture and distribution.

The development of sustainable packaging, better recycling processes and an improved understanding of the complex chemical and biochemical interactions that affect the shelf-life of food products will address many of these challenges.

Further research and development to examine whole waste utilisation is required. This includes the screening of food waste to find and extract valuable biochemicals and investment in anaerobic digestion for improved process control, enhanced performance and increased energy yield. The surface chemistry of membranes should be optimised, minimising fouling and reducing cleaning costs, to improve the economics of recycling aqueous effluent from the food industry.

The procedure of composting waste releases significant amounts of CO_2 and does not contribute to energy generation. This, together with the increasing cost of landfill and the regulation of waste disposal, is a massive driver for alternative uses of food waste, such as anaerobic digestion. Application of a biorefinery concept, where every output is regarded as a potential product rather than a waste stream, will allow the production of energy or high-value products from solid food, agricultural waste and food packaging but will require innovative input from chemistry and chemical engineering.

Resourcing and support

Recruitment into technical, engineering and operational roles is a problem. This will compromise the competitive ability of the UK food industry and its capacity to deliver on consumer expectations.

Placing more emphasis on training, and encouraging people to study science, technology, engineering and maths (STEM) subjects are viewed as ways to increase the supply of skilled scientists and technologists.

It is necessary to promote career opportunities within the food supply chain sector, through improved training of careers advisers and the information resources available for secondary school students, as well as work experience, teaching placements, careers events and media engagement. In addition closer links between food sector industries and universities and their students should be facilitated to ensure graduates have the appropriate skills mix to deliver sustainable food production.

Research priorities for food production and sustainability will require inter- and multi-disciplinary approaches. The industry itself will need to recognise and publicise the increasingly key role of technologists within its operations. Co-ordination of long-term strategic research and effective collaboration between academia, industry and government will be critical to advances in technology.

To enable research at interfaces, higher education institutions (HEIs) need to assess whether they are providing an appropriate infrastructure to enable inter- and multi-disciplinary research. HEIs should look at their structures to identify administrative barriers that impede collaboration, such as different departmental cost structures, and seek harmonisation.

2 Conclusions and recommendations

The solutions to the problems of food production and sustainability are not simple, they will only be found by highly trained people working and leading in the food industry with the appropriate technical background. Only by understanding these problems in scientific and technological terms will the solutions be obvious to those with the power to initiate the required changes across the food chain.

Scientists will have to step back from the bench and learn to think in terms of population, policy, supply chains and product lifecycles. They will have to capture the imagination of teachers, children, and the public and they will need to influence politicians to adapt policies and fund their work.

Whilst education, training and research are the province of the public sector, it must be recognised that the majority of food production, manufacture and distribution is in the hands of the private sector. The necessary competition for profit will need to be balanced with collaboration if any of the overarching problems are to be successfully tackled.

Education and training

There is much confusion amongst employers, potential employees, schools and other interested parties surrounding the profile and breadth of opportunities within the food production sector. Food and drink manufacturers lose out in terms of access to funding and career support to more glamorous or more obvious career opportunities.

- Improvements are necessary in the training of careers advisers and in the information resources available for secondary school students regarding the possible career paths open in modern food production.
- Promotion of career opportunities by the food supply chain sector, through work experience placements, teaching placements, careers events and media engagement will also be required.
- Closer links between food sector industries, and universities and their students should be facilitated to ensure graduates have the appropriate skills mix to deliver sustainable food production.
- To enable research at the interfaces, higher education institutions (HEIs) need to assess whether they are providing an appropriate infrastructure to enable inter- and multi-disciplinary research.

Regulation

Regulation possibly has a bigger role to play in food than in any other industry. However, there is a danger that regulation becomes focused on hazards instead of defined risks; this is a misuse of the precautionary principle. Total elimination of risk is impossible without giving up the benefits of a 'risky' activity. The concept of tolerable levels of risk is used to strike the balance between risk and benefit. However, it must be recognised that perceptions of risk differ widely within society and around the world.

EU food legislation, particularly with respect to the use of chemicals, outputs of chemical sciences and 'novelty' is highly complex and presents significant barriers to rapid approval of new developments and concepts. The precautionary principle is used as the approach to decision-making in the EU, particularly on issues related to food safety and approval of new materials, methods, processes or technologies. The most widely used description is found in Article 15 of the Rio declaration of 1992 in relation to the environment.[2]

"In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

- Regulation should be based on risk, substances should not be banned on the basis of intrinsic hazard alone. Intrinsic hazard is not a good measure of the actual threat that a substance poses to humans or the environment. Risk (which requires both hazard and exposure) is a better measure because it is based on the likelihood that an intrinsic hazard associated with a substance will cause actual harm.

Scientific leadership

Scientific leadership should come from the learned societies, which will need to work together to provide vision, scientific authority, and common guidance. Consumers demand not to be unreasonably affected by the activities of science and technology.

- Science and technology must create a common understanding of benefits and risks through provision of information and by leading the debate in order to build trust amongst all stakeholders.
- Research priorities for food production and sustainability will require inter- and multi-disciplinary approaches. A better dialogue between a number of disciplines including chemists, nutritionists, and molecular biologists must be facilitated.
- For the academic community, a clear communication programme is also required between grant-funders and potential grant-holders in order to optimise funding mechanisms.
- Co-ordination of long-term strategic research and effective collaboration between academia, industry and government will be critical to advances in technology.

Research and innovation

Government should see its role as an enabler not an inhibitor. It must recognise that the need to maintain a choice of foods for a varied and healthy diet, the sustainable use of limited natural resources and profitable production in the entire food supply chain industry are driving forces for investment in new sustainable technology, and for science to discover and create the necessary knowledge and solutions.

- Industry must become more entrepreneurial in changing operating procedures, and in developing and adapting technologies to minimise wastage in materials, energy and water, whilst maintaining and improving the eating quality and nutritional benefit of the foods we choose to consume.
- There are many scientific technologies that can be harnessed and developed to improve food production and sustainability. Research and innovation in the future will require an inter-disciplinary approach, as illustrated throughout the report. For example, chemical and biochemical analysis and diagnostics can contribute to key issues such as nutrition and health, food chain security, and consumer choice. Major challenges in this area include data analysis to improve interpretation of proteomic, metabolomic, genomic, and toxicogenomic research,[3] in addition to validation of new technical methods to national standards.

Chemical science applications

Technologies applicable to the food supply chain can be found in tabulated form within the relevant chapters of this report. These tables identify the underlying science and technology disciplines necessary to develop these research areas, including organic, inorganic, physical and analytical chemistry, structural biology, biochemistry, medicinal chemistry and food science, materials and polymer chemistry and chemical engineering.

3 Background

In the 2008 City Food Lecture, Lord Chris Haskins highlighted the serious possibility of a global shortage of food linked to climate change.[4] To avoid disaster Lord Haskins identified the challenge for consumers, governments, farmers, food manufacturers, retailers and scientists alike. In addition to eating less food, reductions in waste, packaging and the efficient production and movement of food, the most important factor in ensuring an adequate supply of food is embracing and developing technology.

In his first major speech as the newly-appointed Government Chief Scientific Adviser, Professor John Beddington highlighted food shortages as a priority for Government attention, stating that, "science and research to increase the efficiency of agricultural production per unit of land is critical".[5]

Following publication of the Cabinet Office ten-month Strategy Unit project report looking at food policy across UK Government,[6] Hilary Benn, Secretary of State for Environment, Food & Rural Affairs said:

"By 2050 we will need food for a world population that is wealthier and several billion larger. We will need to do this at the same time as adapting to a warming and less predictable climate. And, in addition, we will need to cut the greenhouse gas emissions associated with food production."

The following sub-sections discuss the factors that are contributing to a global food crisis.

Population and economic growth

By 2030 the world's population will have increased by 1.7 billion to over 8 billion, bringing with it the need to meet growing calorific demand.[7] This increase in demand is exacerbated by economic growth in the emerging economies of China, India, Brazil and Russia. As these countries become more affluent this will translate directly into increased food consumption, particularly for high value-added food such as meat and dairy products.[8] Total global food spending grew by 16% between 2004 and 2006 from US$5.5 trillion to US$6.4 trillion.[9]

Price of food and energy

The Food and Agriculture Organization (FAO) Food Price Index has continued to increase since the start of 2008, and by March 2008 it averaged 220, 57% more than in March 2007. Prices of nearly all food commodities have risen since the beginning of 2008 supported by a persistent, tight supply and demand situation. In 2007, the index averaged 157, up 23% from 2006.[10]

Statistics on commodity prices from the Food and Drink Federation (FDF) show that since 2000, prices for agricultural raw material have increased dramatically on the global market, with unprecedented rises occurring in 2006, see Table 1. Reasons for this include extreme weather conditions that have given rise to droughts and floods and thereby adversely affected supplies and increased demand for food, feed (e.g. in rapidly growing economies such as China and India) and for biofuels, resulting in a fall in global stocks.[11]

Table 1: Data from FDF's Agricultural Commodity Prices Report[12]

	2000	2001	2001	2003	2004	2005	2006	2007	Comments
Wheat	68.85	76.43	65.10	78.93	80.30	67.48	78.92	110.92	Quantities sold and weighted average prices of British wheat per tonne of 1000 kilograms computed from returns received by the Home-Grown Cereals Authority each week. Source: DEFRA
Beef	189.81		169.75	173.69	186.32	186.69	201.84	204.37	Price p/kg. Source DEFRA. Note: Figures missing for 2001 due to foot and mouth disease.
Sugar	639.50	668.20	685.10	748.5	742.10	745.10	743.70	739.60	Price £/tonne. Source: DEFRA
Palm Oil	162.21	159.75	245.16	254.99	242.37	195.82	234.52	340.59	Price £/tonne. Price converted from Ringgit at relevant years exchange rate. Source: HGCA

In addition, the increase in oil prices, to $135 per barrel has significant implications for food production as pesticides, fertilisers; mechanical equipment, cultivation, and distribution are largely reliant on or derived from oil.[13]

Climate change

In its latest report, the Intergovernmental Panel on Climate Change (IPCC) states that, "warming of the climate is unequivocal".[14] Climate change is predicted to adversely impact food production and compound problems of growing global food demand. For example, global warming will have significant effects on weather patterns and, consequently, distribution and pattern of rainfall. To appreciate the impact of this on food production it is necessary to consider the total amount of water used. For instance, it takes 1,300 cubic meters of water on average to produce one metric tonne of wheat. This concept, known as virtual water has been defined as 'the volume of freshwater used to produce the product, measured at the place where the product was actually produced.[15] It refers to the sum of the water use in the various steps of the production chain.

Figures from UNESCO-IHE Institute for Water Education, demonstrate the average amounts of virtual water in food.[16]

- the production of 1 kg wheat costs 1,300 L water
- the production of 1 kg broken rice costs 3,400 L water
- the production of 1 kg beef costs 15,000 L water

Land availability

Around 27% of the total global land mass is estimated to be suitable for rain-fed crop cultivation, with only 10% of it currently in use for this purpose.[17] Although this appears to suggest that there is significant room for expansion of food production, the requirements for human settlements, forest, pasture, and nature reserves means that in practice much less land is available for cultivation. It is possible to bring further land into agricultural production. However this is limited to an additional 5-10% of good quality land.[18]

In addition there is a new challenge facing the availability of land, which is the drive to switch from fossil fuel to bioenergy derived from agricultural and forestry sources. Concerns have been raised about the true contribution of so-called first generation biofuels to reducing global warming and that food crops are being used in their production.[19] Indeed, the USDA predicts significant increases in biofuel crop production in the US, EU, Brazil, Argentina and Canada, largely from sugar, maize, vegetable oils and wheat. This growth as a feedstock, is one of the main drivers in the OECD-FAO agricultural outlook 2007-2016, and is one of the causes of increasing international commodity prices.[20]

Food waste

On average we throw away as much as a third of all the food we buy; and at least half of this is food that could have been eaten, if it had been managed better.[21] Overall around 6.7 million tonnes of food waste is produced by households in the UK, which is approximately a fifth of all domestic waste. In economic terms, the cost of food waste is high. Recent figures suggest each household throws away between £4.80 and £7.70 of food that could have been eaten each week, £250-£400 a year or £15,000-£24,000 in a lifetime.

4 Methodology

This report will consider the impact of the chemical sciences on the entire food chain. By this we mean a set of integrated activities beginning with primary production, flowing through food ingredient and product manufacture, to retailer, to the consumer, and finally to waste.[22] It takes a panoramic view, choosing breadth of coverage rather than depth of analysis. Many of the areas considered will benefit from detailed studies of their own, and it is hoped that this report will act as a stimulus for further research.

The objectives of the report are to:

- define what is meant by sustainable food production;
- identify where the chemical sciences can have a key role in guaranteeing the sustainability of food production; and
- contribute to the awareness of the importance of the chemical sciences in guaranteeing sustainable food production.

The scope of the report is focused on the UK and EU to inform policy. However, many of the issues are considered within a global context.

The perspective is one of technology in the chemical sciences:

- current technologies that presently contribute to the sustainability of food production;
- emerging technologies that hold promise for continued sustainability; and
- future technologies, not yet developed, that we might wish to see in 20 years' time to guarantee sustainability in the long term.

In this report we define the chemical sciences to include chemistry, chemical engineering and biochemistry. While related disciplines, such as microbiology and genetics, make crucial contributions to the sustainability of food supply, they are considered only in so far as they support the chemical sciences in their roles outlined above.

In defining sustainability we use the Brundtland Report, which established a benchmark for sustainability:[23]

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Brundtland points out two essential ideas implicit in this definition: the concept of 'needs' (with the emphasis on essential needs of the world's poor), and the sense of limitation imposed on the world's ability to meet those needs, presently and in the future, by the level of technology and social organisation. To be sustainable, therefore, development must meet human needs by increasing productive potential in a way that is equitable to all.

To enhance current and future potential to meet human needs, the following properties are required:

- sustainable development must not endanger systems that support life;
- the creation of waste must be minimised and managed so it does not compromise the integrity of the ecosystem;
- the depletion of non-renewable resources should preclude as few future options as possible; and
- to be sustainable, growth should lead to the reduction of risk.

Accordingly, the principles in this report guiding assessment of changes to the way food is produced are as follows:

- demographics: taking account of and supporting the change in size and movement of the population;
- resources: improving access to and conservation of natural resources;
- production: increasing food production that does not compromise future food security;
- consumer: satisfying the requirements of the consumer;
- technological efforts: recognition that the food supply is not sustainable without scientific advance;

- environment: reducing the ecological impact of food production;
- economics: food production needs to be economically competitive;
- adding value: progress must yield real benefits in terms of capacity to feed the world; and
- regulation: based on risk, including both hazard and exposure.

The investigation of the sustainability of food production has taken the following form:

1. Establishing a conceptual framework to represent food production in the context of sustainability.
2. Developing a questionnaire for use in structured interviews with experts in academia, industry and food industry associations (see Appendix B). Structured interviews were carried out between January and March 2008 with 51 organisations (research conducted by Acumentia Ltd). The interviews were structured to:
   - identify the issues relating to sustainability;
   - discover technologies that could apply; and
   - analyse the implications for the chemical sciences.
3. Desk research was conducted in parallel with the interviews, to support the findings.

The chapters of this report consider the issues as well as the scientific challenges faced across the food supply chain.

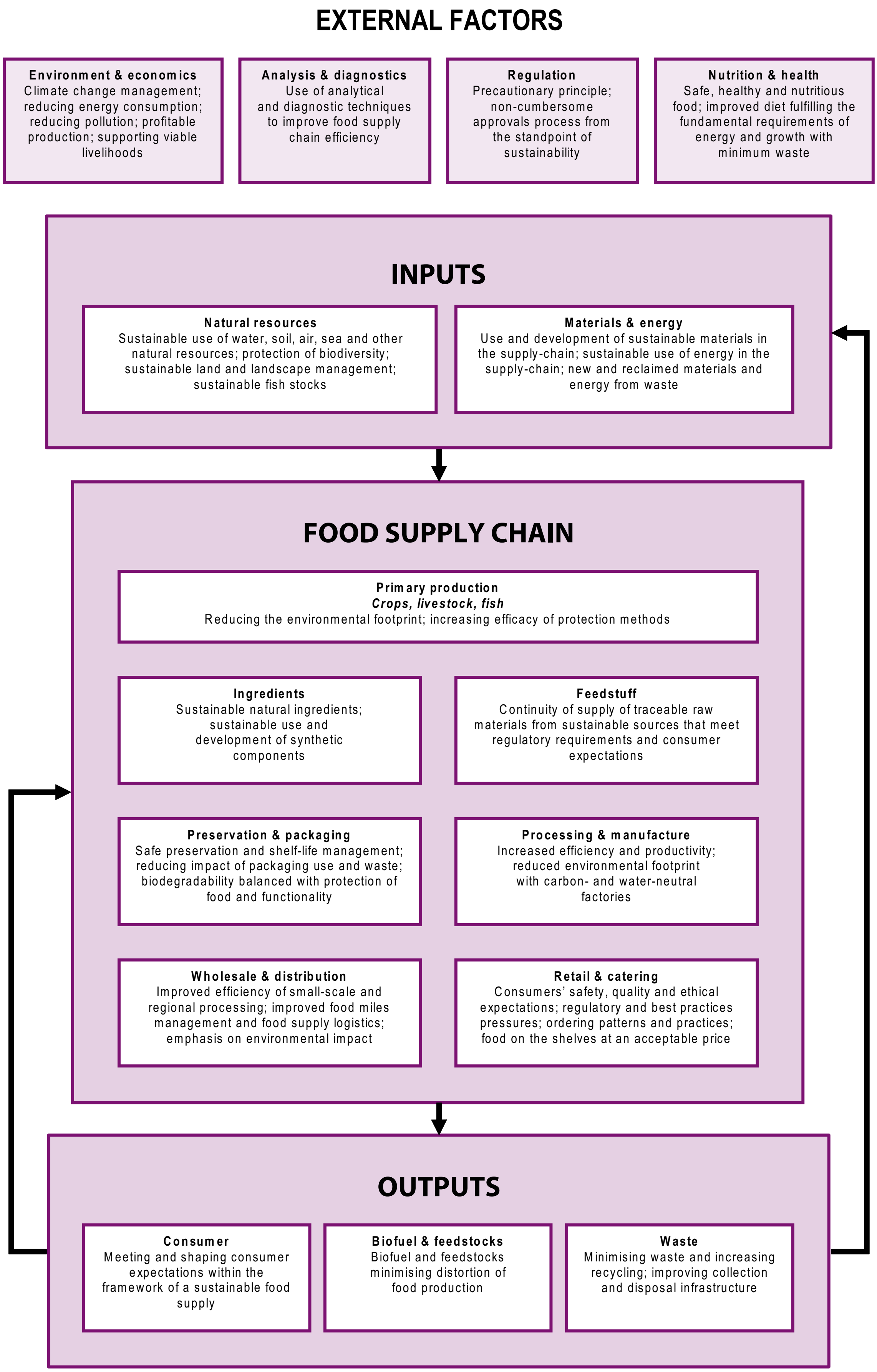
Conceptual framework

The framework within which food production and sustainability is considered in this report is shown in Figure 1. The food supply chain is outlined in context of 'inputs' and 'outputs', and 'external factors'.

Inputs include natural resources, raw materials and energy. The principal output of the food supply chain is the consumer, but waste is also a major output at every stage of the food supply chain. An increase in recycling has produced other outputs in the form of biofuel and feedstocks, some of which can be used to replenish natural resources.

External factors include the environment, economics and regulation, technical applications of analysis and diagnostics, nutrition and health.

Figure1: Conceptual framework



5 Primary agriculture

Conventionally, primary agriculture marks the beginning of the food-supply chain, with the growth of crops, livestock and fish. By 2030 the world's population will have increased by 1.7 billion to over 8 billion, bringing with it the need to meet growing calorific demand.[7] In its Global Environmental Outlook 4, the UN Environmental Programme (UNEP) says that 'to meet the Millennium Development Goals on hunger, a doubling of global food production will be required by 2050'.[24] In addition, world food output must rise to feed the growing, wealthier populations of China, India, Brazil and Russia. The World Bank estimates that cereal production needs to increase by 50% and meat production by 80% between 2000 and 2030 to meet demand. However this will need to be achieved in a changing climate and in a world where natural resources are becoming more scarce.[6]

5.1 Crops

The chemical sciences occupy a pivotal role in primary agriculture, and pressures on global food security mean that agriculture must be more efficient in food production.

Global agricultural output has continued to grow, notably through area expansion in Latin America[8] and yields continue to increase in most countries.[25] As a result, world supply has largely met demand over recent years, with any supply shortfalls due to transitory factors such as weather e.g. drought/floods being met by stocks.[25] However, the underlying consumption of cereals has been consistently higher than production over recent years and this has led to the reduction in stock levels. World demand for cereals grew by 8% between 2000 and 2006 and by 2006 global cereal stocks were at their lowest since the early 1980s.[26] The World Bank estimates that one hectare of land will need to feed 5 people in 2025, whereas in 1960 one hectare was required to feed only 2 people.[18] Organic agriculture, which only allows natural inputs into agricultural production, has grown substantially in the last ten years. However in light of increasing global demand, the FAO does not believe it is a feasible alternative to conventional agriculture.[27]

5.1.1 Climate change

Modern biotechnology should be used to develop crops that are resistant to the effects of climate change, are resilient to fluctuations in water availability, temperature and salt stress, and that also confer positive benefits on crops tailored to the needs of human beings, livestock and fish.

Changes in weather patterns are likely to impact productivity in the major agricultural areas such as the US and South America.[28] Southern parts of Europe are also likely to suffer, whereas northern Europe is likely to benefit from a longer growing season. The consequences of warmer and wetter weather will also increase pest and disease pressures. Changing patterns of rainfall will bring consequences for potable water for human consumption and use in agriculture. Those countries without access to sufficient water supplies to sustain agricultural production will seek to increase imports, putting further pressure on international supplies.

Overall, climate change is predicted to impact food production adversely and to compound problems of growing global food demand. World agricultural GDP is projected to decrease by 16% by 2020 due to global warming.[26] Cereal yields are expected to decline in more than 40 developing countries with average losses of 15% and projections show that land suitable for wheat production may almost disappear in Africa.[29] Whilst the influence of higher atmospheric levels of carbon dioxide could help to limit the severity of climate change effects on productivity, this is not expected to cancel out the losses or keep up with the growing food demand.[30]

It is not likely that the world can avoid the impacts of climate change that will occur over the next 20-30 years, however it is still possible to mitigate the effects by improving planning and infrastructure. It is essential to: decouple growth from greenhouse gas emissions by pricing carbon through tax, trading or regulation; promote low carbon technologies; develop carbon capture and storage technologies; reduce deforestation; improve energy efficiency; and persuade individuals to change their lifestyles to reduce carbon consumption.

5.1.2 Land use

Major opportunities exist for the chemical sciences in addressing sustainable crop production. Research and development for improving the economics of using chemical and biochemical methods to extract cellulose from lignocellulosic fuel crops, such as switch grass, should be pursued as a priority in order to reduce competition for agricultural land.

It is possible to bring further good quality land into agricultural production, although this is limited to an additional 5-10% of land.[18] The additional challenge now being faced is the drive to utilise this arable land for the production of crops for biofuels. The switch from fossil fuel to bioenergy has the potential to reduce greenhouse gas emissions in comparison to burning fossil fuel, while also offering energy security and stimulation of the rural economy. However, concerns have been raised about the true contribution of so-called first generation biofuels in reducing global warming and about the fact that food crops, grown on the same land, are being used in their production.[19]

Many see the way forward as the conversion of cellulosic material to ethanol, known as second generation biofuel. This allows use of the whole plant and more hardy varieties, able to grow on lower grade land with fewer inputs. A Canadian demonstration plant producing 2.5 million litres per annum is a front-runner in cellulosic ethanol.[31] Other demonstration plants are under construction, but significant investment in research is still required to reach commercial viability. Research and development for improving the economics of using chemical and biochemical methods to extract cellulose from lignocellulosic fuel crops, such as switch grass, should be pursued as a priority to reduce competition for agricultural land. Using these methods, plant waste from food crops and forestry will also be used as a feedstock for bioethanol production. This concept is being extended to the development of biorefineries, where plant feedstocks are converted to a range of useful products.

Furthermore, bioenergy production using crops such as *Jatropha*, which can grow on marginal land with low fertility and rainfall, can be used to address desertification and to rehabilitate degraded land from industrial activities or deforestation.[32] Contrary to many popular reports, desertification is actually a subtle and complex process of deterioration that may often be reversible. In the last 25 years, satellites have begun to provide the global monitoring necessary for improving our understanding of desertification. The planting of shrubs and trees protects the land from wind erosion. Soil enrichment with nutrients and more efficient use of existing water resources, coupled to control of salination, are also effective tools for improving arid lands and reversing land degradation.

5.1.3 Productivity

Modern biotechnology should be used to develop crops that are resistant to attack by pests and to environmental stresses, including drought and salinity. In addition, higher yields should be sought through enhanced responsiveness to fertilisers and pesticides. Nutritionally enhanced crops hold tremendous potential to provide significant benefits for human and livestock nutrition, health, welfare, and growth. Regulations in this contentious area must be based on an evaluation of the risk, using sound evidence, and not on a socio-political fear of new technology.

Increasing productivity from existing agricultural land represents a significant opportunity, as existing knowledge and technology can be applied to areas where yields are still below average. Historically, increases in the production of all major crops, apart from soya, have come from higher yield as a consequence of improved varieties, farming practices and knowledge, plus the application of new technologies such as agro chemicals and, more recently, agricultural biotechnology. Since their introduction, crop protection products have played a significant role in the increased yield and without them there would be approximately a 40% loss in agricultural productivity.[33] In wheat, for example, a combination of new varieties and crop protection products has seen a steady increase in UK average yields per hectare over the last 20 years.[34] Crops produced by biotechnology are already contributing to the reduction of greenhouse gases, according to a detailed environmental impact of GM crops 10 years after their introduction.[35]

The introduction of new, better crop varieties generated through conventional breeding or genetic modification has helped to boost yields and improve the quality of many foodstuffs. The higher yields obtained by the genetic modification of crops are believed to have saved millions of square miles of wildlife habitat from conversion to agricultural use.[36]

Farmers are increasingly adopting integrated crop management (ICM) schemes to maximise productivity and minimise a crop's vulnerability to pests and diseases. This entails using 'best practice' through the use of the best crop varieties and husbandry, adopting the best cropping patterns and habitat management and the appropriate use of nutrients (integrated plant nutrient systems, IPNS) and integrated pest management (IPM).

IPNS aims to use an understanding of soil nutrients and biochemistry, in order to improve the precision of inputs to enhance productivity under changing conditions, whilst minimising the potential environmental impact from the use of especially nitrate and phosphate fertilisers. Improving the efficiency of nutrient uptake and utilisation is the challenge of the future.

IPM aims to avoid or reduce the loss of yield due to pests, while minimising negative effects of pest control, by a management process that applies the most appropriate pest control methods and strategy to each situation. IPM promotes primarily biological, cultural and physical pest management techniques, and uses chemical ones only when essential. The use of crop protection products is particularly important in the management of insects and fungal diseases as a last line of defence, because resistance development can leave the farmer with limited or no control measures.

Higher yields should also be sought through enhanced responsiveness to fertilisers and pesticides. Total energy use by UK agriculture (including energy use through the inputs it uses e.g. fertilisers and pesticides) was 2.9 million tonnes oil equivalent in 2006, down over 30% since 1985.[37] The main driver behind the decline of this energy use is the decline in fertiliser application, through improved farming techniques. Research commissioned by the Sustainable Development Commission on the impacts of rising oil prices on the competitiveness of UK agriculture found that there would be a significant increase in agricultural commodity prices, with the highest increases for arable crops.[38] Agricultural producers everywhere will face higher energy costs. However there will be a relatively small impact on agricultural output, with producers passing on increased costs further down the chain. The study recognised that there would be short-term impacts, with a squeezing of profit margins for producers, leading to a fall in production, exiting of some producers and restructuring. These impacts will be more severe if oil prices rise further.

There is still more potential to be realised from using both conventional breeding and plant biotechnology. For example, opportunities exist to enhance a crop's resistance to attack by pests, including pathogens, improve its resistance to environmental stresses, including drought and salinity, and to improve the yield by promoting better root development and improving water use and nitrogen efficiency.[39]

Regulation: pesticides and pest control agents

The main purpose of the pesticides regulatory process is to ensure that registered products meet the pest control claims on the label, whilst not having any unacceptable adverse effect on human health, the environment or subsequent crops. The regulatory decision-making process needs to be proportionate, timely, predictable, and cost-effective, as the regulatory process can act as a barrier to the development of control methods if it does not recognise the risk of investing in R&D and the factors that affect the return from that investment.

For example, in the EU, pesticides are approved or rejected under the Authorisation Directive 91/414/EEC and achieving EU approval of a new active ingredient costs on average 200 million Euros over 8-10 years.[40] With this sort of investment in time and money, the key issue is the scope and time taken for approval in order to ensure an acceptable return on the investment. In addition, developing a pesticide for use in minor crops or for smaller products, such as microbial pesticides or pheromones, the registration fee can be a more significant component of the overall costs.

Those products on the market before the EU-wide legislation was introduced are subject to a review programme. This review has been underway for several years, and saw 330 pesticides withdrawn from the market in 2003 alone (48 of which were approved in the UK). Although there are some new approvals (42 new active ingredients approved by the EC since 1993) there will be a net loss of pesticides, possibly 500 from an original total of approximately 900. The review is due to be completed by the end of 2008.

An amending Regulation 1095/2007/EC is designed to speed up the decision-making process for the remaining active substances (List 3 and 4) of the review programme so that it can meet the 2008 deadline. Further pesticide losses are anticipated once the review is complete.

Directive 91/414 is currently under revision with any changes likely to be effective from 2011. These changes include a proposal to move away from decisions based on scientific risk assessment to hazard based non-approval ("cut-off") criteria. If these political, rather than science-based proposals prevail then there will be further product losses. According to European Crop Protection Association (ECPA) this could lead to the loss of up to 80% of insecticides and 70% of fungicides in the EU, severely impairing sustainable crop protection in Europe.[41]

5.1.4 Soil

Chemical-sensing methods to measure diffuse pollution from agriculture should be promoted alongside remediation technologies. Research should be undertaken to improve understanding of the chemistry of recycling carbon and nitrogen in soil in order to help maintain sustainable agriculture and reduce emissions of nitrous oxide, a potent greenhouse gas.

Maintaining good soil structure is important to ensure high productivity. The yield of crop production is often directly related to the amount of nitrogen and other nutrients available either from natural sources such as nitrogen-fixing bacteria working in symbiotic relationship with legumes or the addition of organic matter (primarily manure) to the soil and applied nitrogen fertiliser. However, not all the available nitrogen is used by the plant; there are also de-nitrifying bacteria in the soil which produce nitrous oxide, which has recently been recognised as a significant contributor to global warming and to potential problems with diffuse pollution of water courses.

Various approaches have been developed in the past few decades to minimise the environmentally detrimental effects of agricultural production. Technologies such as low-till or no-till and the use of cover crops are important. These techniques reduce the demand for energy and water by reducing evaporation, raising the carbon content of soil, improving soil structure, increasing earthworm populations and combating wind and water erosion. Since the introduction of cover crops, no-till acreage has increased by nearly 40%.[36] Research should be undertaken to improve understanding of the chemistry of recycling carbon and nitrogen in soil in order to help maintain sustainable agriculture and reduce emissions of nitrous oxide, a potent greenhouse gas. However, lack of information on agro-ecology and the high demand for management skills are major barriers to the adoption of sustainable agriculture worldwide.

Salinity is one of the most widespread soil degradation processes on the Earth. Salination is often associated with irrigated areas where low rainfall, high evapotranspiration rates or soil textural characteristics impede the washing out of the salts, which subsequently build up in the soil surface layers. Irrigation with high salt content waters dramatically worsens the problem. The accumulation of salts, particularly sodium salts, is one of the main physiological threats to ecosystems as it limits or disturbs the normal metabolism, water quality and nutrient uptake of plants and soil biota, which in turn reduce crop yields.[42]

Unfortunately, salination processes are near to irreversible in the case of heavy-textured soils with high levels of swelling clay. Although a combination of efficient drainage and flushing of the soil by water is often used, the leaching of salts from the profile is rarely effective. Because the reclamation, improvement and management of salt-affected soils necessitate complex and expensive technologies, all efforts must be taken for the efficient prevention of these harmful processes. Adequate soil and water conservation practices, based on a comprehensive soil or land degradation assessment, can provide an "early warning system" that affords possibilities for the prevention of these environmental stresses and their undesirable consequences. Polluted land can be treated in a variety of ways to clean up the soil: washing, extraction and bioremediation are the most common methods used.[43] Chemical sensing methods to measure diffuse pollution from agriculture should be promoted alongside remediation technologies.

5.1.5 Water

A strong focus on developing and improving chemical engineering technologies to conserve and reuse water is required; including the optimisation of water use, treatment of contaminated water, recycling water, desalinating water and harvesting water for irrigation.

Agriculture consumes 70% of global water resources.[44] The expansion of food production necessary to meet demand from the growing population will have serious implications for the world's fresh water resources.[17] Water shortages are already evident in many parts of the world, particularly in Australia, Asia and North Africa. By 2050, up to 7,000 million people in 60 countries will experience water scarcity.[45] Water shortage will force some countries to import food to satisfy domestic demand. Hydroponics, using mineral nutrient solutions instead of soil, is used widely in Israel and Spain and increasingly in northern regions of Europe to alleviate the problem.

There is also widespread concern about water quality, leading the EU to introduce the European Water Framework Directive, which imposes tighter standards on discharges, especially diffuse pollutants such as those from agriculture, which could result in increased farming costs. It is also important to invest in water control facilities to enable more effective monitoring and awareness of water use and water recycling. Other strategies that can be used to increase water productivity are reusing greywater and wastewater for agricultural purposes. Further development of water harvesting and conservation techniques, as well as improvements to crop-water and catchment management, will become increasingly important.

The chemical sciences can help to provide the technological solutions needed to deliver new and improved methods for optimising water use, treating contaminated water, recycling water, desalinating water, preserving water in soil and harvesting water for irrigation.[46]

5.2 Livestock

In the absence of corrective action, the environmental impact of livestock production will worsen considerably. The use of chemical engineering to produce methods of treating supply chain waste to generate energy and biogas should be pursued. Disease in farmed animals should be tackled with research into the development of effective vaccines and veterinary medicines. Modern biotechnology should be harnessed to improve disease resistance, feed conversion and carcass composition.

A recent FAO report states that 1.3 billion people are involved in the world's livestock sector and that it is the fastest growing agricultural sector.[47] Global livestock production faces enormous short-term challenges as income growth in developing countries is creating a surging demand for low-priced meat and dairy products. Total global meat consumption rose from 139 Mt in 1983 to 229 Mt in 1999/2001 and is predicted to rise further to 303 Mt by 2020.[48] The developing world including China, South East Asia, India, Latin America and Africa account for the largest share of this increase with China leading the way with 11% of total world meat consumption in 1983, 20% in 1993 and predicted to rise to 28% by 2050. Coupled to this, developing countries will consume 223 Mt more milk by 2020 than they did in 1993.[48] This puts an increased demand on feed crops and produces an inevitable increase in gas emissions and biowastes, which must be captured and converted into useful nitrogen and energy sources.

5.2.1 Environmental impact

The current total area of livestock grazing and feed-crop production represents 30% of the ice-free terrestrial surface of the planet. The contribution of livestock to climate change amounts to 18% of the global warming effect, this is a larger contribution than worldwide transportation, and is made up of 9% of total carbon dioxide, 37% of total methane and 65% of total nitrous oxide.[47] Livestock also emits around 30 Mt of ammonia globally, accounting for 68% of total emissions and this gas is implicated in soil acidification through nitrification.[47]

It is suggested that livestock production is the biggest single source of water pollutants, predominantly animal waste, antibiotics, hormones, fertilisers and pesticides from feed crops and sediments from eroded pasture. In the United States, the Mississippi River drains almost all the country's industrial livestock farms and animal feed production into the Gulf of Mexico. As a direct consequence the dead zone in the Gulf is the second biggest in the world, comprising thousands of square kilometers where the dissolved oxygen is so low that the water can support only minimal life.[49]

In the absence of corrective action, the environmental impact of livestock production will worsen considerably. Intensive production is characterised by high input use, striving for maximum production to provide food sources for large populations. It is economically competitive due to production and scale efficiencies; however, these must be balanced against the potential for environmental damage, animal health and welfare and waste management issues. Intensive production produces large quantities of industrial waste affecting the quality of both local water supplies and air quality, contaminating the environment with nitrogen, hormones, antibiotics, ammonia and habitat loss. However, there are options for mitigation.

Ruminants produce methane from microbial (enteric) fermentation of feed in their rumens as part of their normal digestive process. Mitigation strategies include manipulation of rumen microfloral properties, diet manipulation to shift fermentation pathways, management for improved productivity (increase per unit of feed) and genetic selection of low methane emitting stock.[50] Research into feed-formulation technology and genetics should be undertaken to evaluate methods of reducing harmful emissions produced by livestock.

The production of biogas by the controlled anaerobic fermentation of animal waste (supplemented, of necessity, by high energy inputs such as maize or food waste) to generate electricity or be used for heat production is being adopted in many parts of the world. Biogas produced in a digester consists of methane (60-70%), carbon dioxide (30-40%) and various amounts of toxic gases including hydrogen sulfide, ammonia, sulfur derived mercaptans and water vapour (1-2%). The trace gases can be corrosive to metal equipment and need to be removed either by chemical methods or by thiobacteria which fix sulfur. The process significantly reduces the levels of pathogens in the slurry, reduces odour and the resulting solid waste is useable as fertiliser. In temperate climates, it is estimated that production of biogas can achieve a 50% reduction in methane emissions; and in warmer climates that figure may rise to 75%.[51]

Technologies needed to counter the problems of environmental impact and waste include a diverse understanding of the chemistry and biochemistry of metabolic pathways, biofiltration, membrane separation, materials science, gas trapping and sequestering technologies, fermentation and enzyme science, as well as the chemical engineering involved in the construction of anaerobic digestion units for the treatment of animal slurry and abattoir waste.

5.2.2 Feed

The impact of the growing consumption of livestock products correlates with an increased demand for animal feed, and is one of the contributory factors in pushing up the price of cereals. The most significant increase has been for wheat, and the price index has averaged 74.5% above the average for 2006/2007.[52] Increases in meat production will result in more direct competition for cereal crops between animal feed, consumption by humans and biofuels.

Enhancing the value of major crops for animal feed through genetic modification promises to give better animal performance and health, but also lower feed costs and more affordable livestock protein products.[53] Improvement efforts will focus on protein quality, particularly amino acid balance; better digestibility of fibre and starch; and lower anti-nutritional factors – such as stachyose and phytate, which monogastric animals cannot digest well, or at all.

Successful current examples of nutrient enrichment include high-lysine maize, low-phytate maize, and high oleic acid soya beans. Other targets include high-methionine soya beans, high-oil maize and low-stachyose soya beans – all of which could provide significantly improved feed characteristics and animal performance. Another intriguing opportunity is the possible future development of antibody-containing soya beans which, when fed before slaughter, could combat such pathogens as *E. coli* and *Salmonella* spp.

Synthetic amino acids have been used in animal feed for many years since the first chemical synthesis of DL-methionine in the 1950s for inclusion in poultry feed. L-lysine production by fermentation began in the 1960s in Japan, followed by L-threonine and L-tryptophan in the late 1980s. The adoption of modern biotechnology has revolutionised organic synthesis, and has significantly reduced the costs of amino acid production, offering the potential for further developments as new enzymes and microbial agents are discovered and developed.

Feed technology relies on nutritional science, micronutrient and phytochemical research, anti-nutritional factors, chemical/microbiological contaminants, analytical monitoring/diagnostics and feed compounding. By-products from the processing of crops for food (e.g. vegetable oil) and for industrial uses (e.g. alcohol) will continue to increase and to be a major source of feed protein.

5.2.3 Disease control

Livestock diseases (parasites, bacteria, viruses and other agents) affect animal welfare, reduce productivity and in the case of zoonoses can be transmitted to humans. These zoonoses affect hundreds of thousands of people each year, especially in developing countries, where diseases are estimated to reduce animal productivity by around 25%. Intensive livestock production results in increased stress in animals and as a consequence weaker immune systems and a greater susceptibility to disease. The high density of animals results in rapid transmission of disease(s). Disease management can be achieved through changes in animal husbandry and/or the use of antibiotics and vaccines. In some intensively farmed livestock, antibiotics and chemicals are added to feed to control bacteria and parasitic infections. The rise of antibiotic resistance and legislation has restricted the practice in food production animals. Vaccine development is an alternative to antibiotic use. Improved vaccines and adjuvants (substances that improve the efficacy of vaccines and therapeutics) are being developed to tackle a range of diseases, including those emerging in industrialised countries as a consequence of climate change.

The use of hormones as growth promoters for livestock was banned in 1988 by the EU who included a ban on import of beef from the US because of the potential risk to human health. The US and Canada permit the use of six growth hormones in beef production and the use of recombinant bovine growth hormone (rBGH or BST), which increases milk production in dairy cattle. There is concern over the environmental effects of hormone residues in meat on human health but also on the surrounding environment i.e. water supplies and the effect on the reproductive biology of aquatic species.[54]

In livestock production, the control of disease is critical to sustainability. Pharmaceutical chemistry, veterinary science, vaccines, chemical and biochemical diagnostic assays, disinfectant chemistry, efficacy testing and mechanisms of biocidal activity all play a central role.

Regulation: veterinary medicines

The evaluation of new animal medicines in the EU is limited by regulation that requires information on quality, safety and efficacy. In the USA, quality and safety are deemed to be sufficient – efficacy is assumed to be determined by the market (i.e. if it doesn't work, it won't be successful). In the EU, efficacy trials increase the time of adoption of new products and increase costs. For example, postweaning multisystemic wasting syndrome (PMWS), a fatal disease that wipes out pig herds in the UK and other EU countries, can be treated by vaccination. The first vaccine developed took 10 years to licence in the EU. In the USA, PMWS was first seen in pigs in 2006, and at least four vaccines were made available and authorised within two years. It costs in the region of £500m to have a product approved for animal use. These costs are prohibitive for most companies, with the result that medicines are not developed and animals contract diseases that transfer to the human population.

There is growing evidence that this is the origin of Methicillin resistant *Staphylococcus aureus* (MRSA). Following the discovery of a new type of MRSA, recently emerged in the Netherlands and labelled NT-MRSA, farmers there are now confined to isolation units when admitted to hospital. The first isolate was found in 2003, and since then it has been found with increasing frequency, and it correlates with the density of pig populations. This association was confirmed by the results from a case-control study, which show that NT-MRSA is significantly related to contact with pigs. In addition, a significant association was found with cattle. Screening of a representative sample of pigs in the Netherlands was recently performed and showed that nearly 40% of the pigs were colonised with a comparable strain of MRSA (MLST 398) with more than 80% of pig farms affected.[55]

When the intensive international transport of pigs is considered, it is unlikely that this situation is limited to the Netherlands. The implication is that those working or living in close contact with pigs or cows are at increased risk of becoming colonised and infected with MRSA. Infections can be severe, as indicated by the hospital admission rate.

It is therefore imperative that the necessary legislation required to control new medicines does not act as a barrier to their development. Otherwise, the potential for animal derived infectious diseases in the human population will increase.

5.2.4 Genetic modification

The selective breeding of animal species to enhance particular genetic traits has been taking place since the first domestication of animals thousands of years ago. The livestock we see today, and the variations within livestock species adapted to different environments and human needs, are the result of this process. The large-scale sequencing and genome mapping of major livestock species in the last decade has improved the understanding of animal genetics. Studies have focused predominantly on improving growth efficiency and on improving human nutrition and human healthcare. Examples of GM farm animals include 'Enviropigs' that can utilise phytate in their diet as a source of phosphate (otherwise it is excreted) and therefore reduce the phosphorous content of their manure by up to 60%,[56] and the expression of a bacterial enzyme, lysostaphin, in cattle to reduce the incidence of mastitis.[57]

Consumer acceptance of GM foods varies among countries, with more positive attitudes found in the US, Canada and Japan than in Europe. The acceptance of GM crops has proved problematic in the UK and Europe; the acceptance of GM animals in the food chain (other than those fed GM crops) may provoke a stronger consumer reaction. The main consumer concerns are related to the unknown long-term health effects, safety in terms of accidental release into the environment, 'unnaturalness' and ethical and animal welfare problems. There are concerns over who benefits, the consumer view being that the producers are the main beneficiaries. However the benefits of modern biotechnology include improved disease resistance, feed conversion and carcass composition. The true benefits to all must be balanced against any potential risks through a better dialogue between consumers, the food industry and government.

Regulation: Genetically Modified Organisms (GMOs)

There are two principal sets of legislation for approving GMOs in the EU: Directive 2001/18/EC on the deliberate release into the environment of GMOs; and Regulation (EC) No 1829/2003 on genetically-modified food and feed.

Regulation (EC) No1829/2003 introduced a single risk assessment process for GMOs in the EU by centralising it with the European Food Safety Authority (EFSA). However, the final decision on whether or not to approve a GMO is taken by the EC, following publication of the EFSA opinion, a validated event-specific detection method, and availability of certified reference material. As part of the approval process under the (EC) No 1829/2003, the Member States must vote on the Commission proposal at the Standing Committee on the Human Food Chain and Animal Health. If no decision is reached, the Commission must then present the proposal to the Council of Ministers of the Member States who have 60 days to reach a decision. In the absence of a decision, the proposal moves back to the Commission to make the final decision.

Since its introduction, an increasing number of applications for the authorisation of new GMOs (for import, food, feed, and cultivation) have been introduced through this more recent legislative route. However, European GM approvals remain few and far between, with EuropaBio (the European Association for Bioindustries) stating in December 2007 that "there are many products that have gained approval worldwide but that are still stuck in the European system. These are traders' crops, and so the slow process causes problems for them and results in a shortage of supplies for Europe."

In December 2007, the German agriculture minister suggested that the EU make decisions to approve GM plants in Europe purely on the basis of science, and do away with political voting on the matter. Currently, proposals are subjected to voting by the Council of Ministers and by the European Commission, resulting in the politicisation of science. Separation of science (risk assessment) and politics (often the driver for risk management) would therefore assist in allowing GM technology to benefit consumers and the environment.

5.3 Fish

The growth of aquaculture over the next two decades will involve intensification, improvements in productivity through breeding programmes, modifications of the cultivated organism and feed research to reduce the dependence on fish oil and meal. Water recirculation and aeration technology, coupled with the controlled use of antibiotics, can ease the stress caused by intensive farming; but, unlike treating human or other animal diseases, few drugs are available for treating diseases in fish because of environmental concerns and a relative lack of knowledge about many fish diseases.

The most recent global assessment of wild marine fish stock found that, out of the nearly 600 species monitored by FAO, 25% are over-exploited and 52% are fully exploited. 20% are moderately exploited and just 3% are ranked as underexploited. Most wild fisheries are at or near their maximum sustainable exploitation level, and further increases could cause lasting damage to fisheries and marine ecosystems.[58]

There is little chance of increasing the global catch of fish without further damaging marine ecosystems. The future shortfall in the supply of fish protein must be met by aquaculture. Aquaculture is the fastest growing food-producing sector and its growth over the past 25 years has averaged 9% per annum over the past decade. In 2004, 43% of the global fish supply came from farmed sources, with the greatest proportion located in Asia, representing almost 90% of all farmed fish.[59]

Technological development of aquaculture farming methods is critical to the efficiency of the industry. The growth of aquaculture over the next few decades will involve intensification, improvements in productivity through breeding programs, modifications of the cultivated organism and feed research to reduce the dependence on fish meal, disease control technologies, farm design, and water recirculation technology.

5.3.1 Environmental impact

The impact of climate change on the sustainability of fish-supplies is a major concern for the world's fishery-dependent populations, many of whom live in areas vulnerable to climate change. Climate change has altered, and continues to alter, the abundance and distribution of fish stock in EU waters.[60, 61]

Intensive aquaculture can have positive effects on fish health and the environment if managed properly, creating less demand for land and water per unit of output. Water recirculation, aeration and oxygenation technologies reduce the risk of disease and also mitigate against water pollution. In fresh water fisheries, less river water is used in a recirculating water system, so reducing the environmental impact of discharge of phosphorous and nitrogen to rivers. Management techniques, including rotation of culture species, polyculture (in which several species are grown together) or aquatic species farmed in tandem with a land based crop such as rice, can also improve the efficiency of production. In marine systems, treatments with insecticides can affect other marine organisms, as can fish waste. Waste management systems need to be developed to reduce their effects on coastal species and human populations.

5.3.2 Feed

Besides being used as human food, nearly one third of the world's wild caught fish is converted to fishmeal and fish oil and used in feed for livestock and farmed carnivorous fish.[62] In 2005 aquaculture accounted for 45% (47.8 Mt) of global fisheries production (107 Mt). Of the predicted 172 Mt of fish required in 2015, 80% will be required for food and the remaining 20% for fishmeal or fish oil for animal feeds and non-food uses. To meet these requirements a large increase in aquaculture will be required as caught fish levels remain static or decrease.[59]

Almost all finfish species farmed are dependent on reduction (industrial) fisheries to produce fishmeal and fish oil. If the aquaculture industry grows as predicted the need for marine raw material will not be able to be met by increasing industrial fisheries. Reducing the dependence of aquaculture on fish feed and fish oil is a key research requirement, by replacement of fishmeal with proteins/oil derived from vegetable sources (soy, rape, palm etc) providing that they come from a sustainable sources.

5.3.3 Disease control

The FAO considers that disease is the biggest single impediment to aquaculture development. Infectious diseases caused by bacteria, viruses and parasites are a primary concern, and whilst aquaculture does not necessarily create disease, high stocking densities can lead to outbreaks of diseases that occur only at low levels in natural populations. Water recirculation and aeration technology, coupled with the controlled use of antibiotics, can ease the stress caused by intensive farming; but, unlike treating human or other animal diseases, few drugs are available for treating diseases in fish because of environ¬mental concerns and a relative lack of knowledge about many fish diseases.

5.3.4 Genetic modification

Selective breeding of fish began about 20 years ago and is still in its infancy. Significant productivity increases have been achieved for salmon, trout and tilapia, and there is still considerable scope using classical selection techniques to make further improvements. Transgenic salmon, catfish, carp and tilapia, modified with fish-derived somatatropin, have been developed to reach harvest weight sooner than non-GM counterparts. The main traits to be altered are growth rate, cold tolerance, disease resistance and sterility. Transgenic fish, to date, have not been approved for human consumption.[63]

5.4 Chemical science applications

Technologies applicable to primary agriculture can be found in the following table. This table also identifies the underlying science and technology disciplines necessary to develop these research areas. A multidisciplinary and interdisciplinary approach is essential, with input identified from organic, inorganic, physical and analytical chemistry, structural biology, biochemistry, medicinal chemistry and food science, materials and polymer chemistry and chemical engineering.

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Analysis of climate change parameters, e.g. greenhouse gases and seawater salinity, generates input for predictive models, which can identify changing conditions for agronomy, providing valuable data for the planting of new crops.				✓			
Precision agriculture at the field level.				✓			
Engineering tools (e.g. sensors) for on-farm practices e.g. grain drying, seed treatment and crop handling.				✓			
Formulation engineering for delivery and minor component release and reduced waste (i.e. pig and fish –phosphorous).			✓	✓		✓	
Genetic analysis for conventional breeding – Quantitative Trait Loci (QTL).					✓		
Formulation technology to ensure a consistent, effective dose of agrochemicals is delivered in time and quantity.			✓	✓		✓	
Development of rapid in situ biosensor systems that can monitor crop ripening, crop diseases and water availability to pinpoint nutrient deficiencies and improve the quality and yield of crops.				✓			
Development of field-based, rapid methods including dipsticks, immuno-labelling methods and lab-on-chip devices for environmental analysis to detect pollutants from primary production, such as pesticides or nitrates, that will help to pinpoint sources of diffuse pollution and allow methods for remediation to be put in place.	✓	✓	✓	✓			
Harnessing of analytical chemistry to design rapid, real-time screening methods, microanalytical techniques and other advanced detection systems to screen for chemicals, toxins, veterinary medicines, growth hormones and microbial contamination of food products and their raw materials. To detect that they are not contaminated at source or during distribution, storage and processing, and that they contain required nutrients and are safe and fit for purpose, thereby avoiding their (re)processing, transportation or recall, and avoiding waste.	✓	✓	✓	✓		✓	
DNA analysis for animal genotyping to establish breed quality and authenticity.				✓	✓		
Understand feed in animals: feed conversion via nutrigenomics of the animal and bioavailability of nutrients.				✓	✓		
Development of pesticides using pheromones, semiochemicals and allelochemicals as a starting point for pest control strategies.	✓				✓		

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of fertiliser formulations able to improve the retention of nitrogen in soil.	✓						
Understanding the metabolomics of spoilage of crops and food, to reduce losses.	✓				✓		
Development of alternatives to ethylene for ripening control.	✓	✓			✓		
The development of chemical treatments to remove pathogens from raw ready-to-eat crops without affecting eating quality or nutritional content.	✓			✓			
Low energy synthesis of nitrogen and phosphorus in fertilisers, finding alternatives to Haber-Bosch.	✓	✓	✓				✓
Understand plant growth regulators.					✓		
Secondary metabolites for food and industrial use.					✓		
Understand the impact of nutrients at the macro and micro level.					✓		
Use of modern biotechnology (including genetic modification) for the development of plants that: are capable of withstanding the effects of climate change (such as increased drought resistance, and salt resistance); have improved nitrogen-fixing characteristics; enhance nutrition (by production of vitamins and omega-3 oils); use fertilisers more efficiently; have reduced anti-nutritive factors; resist disease and pests; and survive on alternative nutrients, all of which will help to provide the basic staples at affordable prices to an increasing world population.				✓	✓		
Genetic engineering of animals that will help to improve disease resistance, reduce green house gas emissions, improve nutritional content and flavour of meat and improve feed conversion efficiency; vigorous pursuit of groundbreaking developments such as the EnviropigTM; engineering animal feed to improve performance and health, reduce feed costs and produce more affordable protein.				✓	✓		
In aquaculture, improvement of reproductive success, shelf-life of the finished product and resistance to disease; development of favourable behavioural traits and built-in osmoregulation; development of a high-yielding omega-3 soya bean to replace industrial fish feed and reduce industrial fishing.				✓	✓		
Improved understanding of the mechanisms involved in competitive exclusion and its application to intensive animal rearing.					✓		
Understanding and exploiting biochemical plant signals for the development of new crop defence technologies.					✓		

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Improved understanding of the mechanisms involved in toxin production in crops and other plants.					✓		
Optimisation of farming practices by understanding the biochemistry of soil ecosystems, for example the chemistry of nitrous oxide emissions from soil, and partition between soil, water, vapour, roots and other soil types.					✓		
Development of bioremediation technologies using microorganisms, and other living organisms, to degrade or detoxify environmental contaminants in soil, so reclaiming it for agricultural use.				✓	✓		
Development of chemicals for soil purification, e.g. sequestrants to complex toxic metals.	✓	✓		✓			
Improvement in the understanding of carbon, nitrogen, phosphorus and sulfur cycling to help optimise carbon and nitrogen sequestration and benefit plant nutrition.					✓		
Improved understanding of methane oxidation by bacteria (methanotrophs) in soil to help in the development of methane fixing technologies.					✓		
Development of more efficient processes, allowing the reuse of treated effluents and greywater, and the desalination of seawater for irrigation.				✓			✓
Improved irrigation technology to increase precision, reduce losses, and reduce microbial contamination from soil-splash.							✓
Development of more efficient crop drying technologies, especially in tropical countries, which do not contaminate raw materials.							✓
Improved understanding of algae aquaculture technology to produce new human and animal food and high-value food ingredients, such as beta-carotene.	✓				✓		✓
Application of enzymatic and chemical modifications of lignified animal feed to improve access to celluloses and increase nutritional value.					✓		✓
Use of mass, heat and energy transfer principles, combined with advanced data handling, to minimise losses of product, water and energy throughout the supply-chain.							✓
Development of improved slaughtering techniques and processes using less energy to recover by-products and reduce waste. Reduction of carcass contamination from abattoirs by developing technologies such as hand-held steam pasteurisation.							✓

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Understanding of soil structure, material mechanical properties of soils and nutrient flow.				✓	✓		
Development of new vaccines and vetenary medicines to treat the diseases (old, new and emerging) of livestock and farmed fish, i.e. zoonoses.						✓	
Development of novel ways of collecting samples from animals to replace blood-samples, that will improve the quality of management and animal welfare, e.g. monitoring saliva to detect animals on heat.				✓	✓		
Understanding the fundamental chemistry and biochemistry of anaerobic digestion and the generation of biogas to improve yield and efficiency.					✓		✓

6 Food processing and manufacture

The food and drinks industry is the EU's largest manufacturing sector, with a turnover in 2006 of €870 billion, and the largest employer, with 4.3 million people employed in the sector in 2006.[64] In the UK, food and drink manufacturing has a turnover of almost £74 billion and value added of £21.5.billion. Exports of unprocessed primary products, at £700m, are very low, implying that virtually all of agriculture's £14.8 billion output and its 534,000 workforce depend on the UK market. UK food retailers and caterers together employ an additional 2.5m people.[65]

6.1 Raw materials and ingredients

Research should be undertaken into innovative sourcing of raw materials and alternative uses. The application of novel enzyme chemistry and technology for use in ingredients, processing and preservation is a key area for development. This includes product structure and flavour release, taste and textural development and product changes at different stages of processing.

Continuity and security of supply of key raw materials for use in food processing and manufacture is a critical sustainability issue and increasingly so with rising prices of crops such as wheat. In order to identify alternative/parallel supplies of raw materials it is necessary to understand at the molecular level what determines the key quality characteristics and attributes of a raw material, and its effect and performance in the final foodstuff. Ultimately this will enable improvements in the efficiency of manufacturing processes and will optimise control. Making use of alternate types of raw material through reformulation and new product development (NPD) could, for example, identify alternative sources and forms of high protein products and improve the palatability of existing meat analogues such as Quorn™.

Food materials have a complex texture and structure, and greater understanding is needed of the interaction between food components if we are to preserve the pleasant sensation of eating, whilst modifying the calorie content and increasing the nutritional benefits. This includes understanding product structure and flavour release, taste and textural development and product changes at different stages of processing. For example, a number of chocolate processes are based around crumb, produced from milk, sugar and cocoa liquor. The unique flavour and 'mouth feel' developed in the process, and the phase change produced during the heating of the milk, is critical to the quality of the final chocolate.

Food materials are not stable, and their quality attributes change as goods move from the field to the processing site. Development of quality sensors as rapid diagnostic tools will maximise processing performance, against variable input materials.

An increasingly important issue for raw materials and ingredients is the nutritional and health demands now required from food products. This generates new product development (NPD) activity to produce 'healthy food', which in turn drives the sourcing of materials and the development of nutrient-rich food at the primary production level. Research in NPD to find healthier/alternative ingredients include sweeteners (particularly high-intensity sweeteners), new sources of triglycerides, and carbohydrates with modified performance. In addition, greater understanding of how material properties of ingredients and foods influence the bioavailability of nutrients is required.

Regulation: Novel food and novel processes

Novel food is defined in the Novel Foods Regulation (Regulation (EC) No 258/97) as food, or an ingredient of food, that does not have a significant history of consumption within the EU before 15 May 1997 (when the first Novel Foods legislation came into force). It can be newly developed, innovative food; food produced using new technologies and production processes; or food that has been traditionally consumed outside the EU.

Novel food is only approved for use in the EU if it does not present a danger to public health, is not nutritionally disadvantageous when replacing similar food, and is not misleading to the consumer.

Novel food must undergo a scientific assessment prior to authorisation, to ensure its safety: the authorisation sets out, as appropriate, the conditions for its use, the designation as a food and/or food ingredient and the labelling requirements.

Regulation (EC) No 258/97 lays down harmonised measures for the authorisation of novel food, which means that once a foodstuff is approved for marketing in the EU, it can be sold in any member state. However, a member state can suspend or provisionally restrict the marketing and use of any novel food if it believes it to constitute a health hazard according to the safeguard provisions of the General Food Law (Regulation 178/2002). The member state authorities must inform the EC, which then carries out an investigation into the protective measure of the member state. If a food is found to pose any risk to consumers, the EC can immediately suspend its authorisation for marketing in the EU.

A 2002 stakeholder consultation showed the need to update the current provisions for novel food, to create a more favourable legislative environment for innovation in the food industry in line with new technological developments and scientific advice, and to facilitate better internal and external trade in foodstuffs. The aim was to increase the efficiency of the authorisation procedure, enable a quicker delivery of safe, innovative food to the market, and remove unnecessary barriers to trade, while still ensuring food safety. However, it was also to allow the consumer to benefit from a wider choice of safe novel food.

An updated regulation proposed in 2006 seeks to create a centralised authorisation system, allowing greater clarity for applicants seeking authorisation for a novel food, and simplifying and speeding up the process for authorisation. The original regulation also needed to be revised to reflect the fact that it no longer covered genetically modified organisms (GMOs), which have been dealt with under separate legislation since 2003. The proposal also sets out data protection rules, which aim to protect newly developed foodstuff once authorised, and encourage companies to invest in developing new types of food and food production techniques. Moreover, a notification procedure is introduced for food which has not been traditionally sold in the EU but which has a safe history of use in third countries. If safety in a third country can be demonstrated, and there are no objections from member states or EFSA, the food will be allowed to be placed on the market on the basis of a notification from the third country operator.

EFSA is responsible for carrying out the risk assessment on the novel food applications, while the EC manages the dossiers of each applicant, putting forward a proposal for the authorisation of novel food that is found to be safe. The applicant may make one application for approval covering all the possible uses of the substance in question. A total of 53 applications had been made between May 1997 and May 2004. By May 2004, 14 novel foods were approved to be commercialised in the EU.[66]

The authorised novel food includes products traditional to third countries such as 'noni juice' (made from a Tahitian plant), and food produced using technical innovations, such as oils and dairy products enriched with phytosterols or phytostanols to reduce cholesterol. Other examples include 'salatrim' (a reduced-energy fat), Docosahexaenoic acid (DHA) rich oil, and a high-pressure fruit juice, the last of which is an example of a food derived from new production processes.

To date three applications have been refused under the Novel Foods Regulation, and these were largely due to missing data in the dossier or to safety concerns.

Novel food is subject to the general labelling requirements (Directive 2000/13/EC). Specific additional requirements for the labelling of novel food may also apply, if necessary, to inform the consumer properly. The label must mention the name of the food, and, where appropriate, specify the conditions of use.

6.1.1 Traceability and authenticity

Counterfeiting

The issue of counterfeit ingredients and adulteration has become increasingly important and relevant within supply chain sustainability, as sourcing materials becomes ever more difficult and expensive with the rising cost of commodities. The marketing of fake goods does considerable damage to right holders and more attention is being drawn to the dangers to the consumers' health and safety.

European Commission, Taxation and Customs Union show that in 2006, 54 cases of counterfeit foodstuffs, and beverages were registered.[67]

Counterfeiting and tampering can undermine consumers' trust in the quality and safety of a branded food product, leading to a loss in market share. In response, industries have turned to new forms of packaging and intelligent labelling to ensure consumers and customs can check for authenticity.

Food analyses and diagnostic tools should continue to be developed to ensure food authenticity and traceability. Examples include holograms, embedded security threats, colour change inks and paper watermarks. Radio frequency identification (RFID) is an emerging tracking technology. It facilitates automatic identification, relying on storing and remotely retrieving data, using RFID tags or transponders.

Allergenicity

The EU Directive 89/2003 recognises that serious allergic reactions can be caused by certain food, and requires pre-packed food sold in the EU to show if it contains any of 14 listed allergenic foods . However, errors in packing and labelling of food were the biggest cause of food and drink product recalls in 2007.[68, 69] Both enzyme-linked immunosorbert assay (ELISA) methods or DNA analyses using polymerase chain reaction (PCR) are commonly used in allergen analysis

EFSA's Scientific Panel on Dietetic Products, Nutrition and Allergies (NDA) stated in 2004 that "in no case is the available evidence sufficient to establish an intake threshold below which allergic reactions are not triggered, or to predict reliably the effect of food processing on allergenic potential. While it is possible that specific derivatives of these known ingredients might not trigger an allergic reaction, this would need to be evaluated on a case by case basis."[70]

The future approach to allergen labelling depends to a significant extent on the outcomes of the ongoing EuroPrevall project.[71] This is studying various aspects of allergy, including true prevalence links between allergy, hygiene and disease, and has as one of its aims the determination of thresholds eliciting symptoms.

Genetic testing

DNA testing has been applied to detecting GMOs, identifying allergens, determining the species of meat and fish, identifying basmati rice (particularly checking for adulteration with other species), checking cattle paternity for animal registration purposes, rapidly identifying microorganisms, and establishing food authenticity. The difficulties lie in the high cost of equipment, the need for laboratory facilities that minimise the opportunity for cross-contamination, and the employment of highly-trained analysts.

6.2 Manufacture processes

Processing areas identified for improvement include heat-transfer systems, low energy separation technologies, rapid heating and chilling technologies and fermentation technology. Innovation in engineering can increase operational efficiency, improve use of energy and the management of water and waste, and develop extraction technologies for the recovery and use of by- and co-products.

Nano scale techniques offer major contributions to biosensors throughout the food chain and may lead to the development of new functional materials, food formulations and improvements in diet.

Considering the whole manufacturing process, the development of small-scale but highly efficient processes, with flexibility to accommodate small production runs, is necessary to meet the demands of retail production under current commercial arrangements, in addition to mitigating the environmental impact of transporting goods. Thus miniaturised processing systems for local use need to be developed.

Within the manufacturing process itself, raw materials move through a variety of stages, or unit operations. Goods are received, stored and transferred; ingredients are mixed, heated (fried, boiled, baked, etc) or cooled (frozen/chilled), shaped, transferred, possibly heated or cooled again, transferred, shaped or portioned (e.g. sliced), packed and stored. At each of these steps there is the potential to improve sustainability, particularly in managing waste, including efficiency of energy during heat exchange, of ingredients through process control, and appropriate portioning. A discussion on portioning would consider the role of chemical engineering in producing new hygienic portioning methods, for example laser cutting, water cutting, and ultrasonics.

Common themes underlying all these factors are improvement in operational processing efficiency and the raising of production standards. Examples are the efficiency of high energy thermal processes (especially refrigeration), the development of non-thermal processes to preserve food, management of water and waste and the development of extraction technologies for the recovery and use of by- and co-products from waste streams.

Key unit operations are heat-transfer systems, low-energy separation technologies, rapid heating and chilling technologies and fermentation technology.

Research is needed to understand product changes at different stages of processing and throughout the shelf life of goods, particularly for ambient stable products of long life, e.g. canned or dehydrated goods. This knowledge will help improve food safety and food process safety, through understanding how bacterial load changes and how dangerous compounds are produced through processing. The new targets are not just cost savings, but minimisation of waste in materials, energy and water use.

Nanotechnology will provide the food industry with more capability and precision, which will in turn make processes more efficient and sustainable, both in manufacturing and in subsequent digestion. The need for mechanisms to control the delivery of functional ingredients within the body has focused on the development of nanostructures such as:

- the use of proteins to lower fat content in emulsion-based products with no detrimental end-product organoleptic effect;
- the use of acid-sensitive alginates that create a 'full' sensation inside the stomach, slowing down gut passage rates;
- engineering taste sensations into high fat products or nutritional benefits;
- nano-filtration, already applied to the filtration of microorganisms from food;
- filtering out components such as lactose from milk and replacing it with another sugar, creating milk suitable for lactose-intolerants; and
- encapsulation systems used to provide protection against environmental factors, and controlled release and nutrient delivery.

6.2.1 Flavour and physical quality

Flavour analysis can play a major part in maintaining the quality and consistency of food, and in optimising recipe and processes to make use of flavours in the most efficient way. Chemical analysis of volatile flavours (or aromas) in a food matrix can be demanding, because the key odour-active compounds are often present in trace amounts and can be embedded in food or extracts, along with higher levels of other volatile compounds.

However, as flavour analysis has delved deeper into the realms of flavour generation and delivery, more powerful methods such as metabolite profiling and metabolomics have been used. Model mouths have been developed that monitor the flavour released from food. More recent techniques that can characterise volatile compounds in a mixture without prior chromatographic separation, such as atmospheric pressure chemical ionisation mass spectrometry (APCI-MS), proton transfer reactor mass spectrometry (PTR-MS) and resonance enhanced multiphoton ionisation time-of-flight mass spectrometry (REMPI-TOFMS) have been used to study flavour release during food processing or food consumption. A development of APCI-MS that samples air from the nose or mouth during eating, or from the headspace above the food, has become commercially available as the mass spectrometry (MS) nose; it is able to detect flavour concentrations as low as 10 parts per billion (1 in 108).

The visual appearance of food is a major factor in satisfying consumer judgement of food quality. Visual inspection of food in production is time-consuming and expensive and only provides qualitative assessment. Various instrumental techniques applicable on-line include tristimulus colorimetry and machine vision systems involving cameras and image analysis.

Light microscopy and electron microscopy are used to examine the microstructure of food, from primary production to the finished food being consumed. These techniques can look at natural surface features or at internal microstructural features by thin-sectioning or by fracturing and etching.

Measuring the rheological behaviour of raw ingredients and processed food during manufacture can enable optimum process efficiency and desirable sensory perception of both texture and flavour. Rheometry can be used for more fluid and homogeneous food to characterise flow behaviour and visco elasticity. More solid-like samples are frequently characterised using mechanical instruments such as dynamic mechanical thermoanalysis (DMTA) or food texture analysers.

Laboratory-based instruments such as differential scanning calorimetry (DSC) are used to examine thermal transitions associated with phase changes, such as the melting and crystallisation of solids (particularly fats, sugars and ice) and changes of state associated with transitions from rubbery to a brittle, vitreous consistency. The results can give valuable information on the polymorphic form of fat crystals in fat-based products, and glass transitions affecting the texture of food of low to intermediate moisture. These analyses generally are aimed at improving sustainability by optimising product quality through an understanding of physical changes that are occurring during processing.

Many sensors and probes are already used in–line for food process control to measure physical parameters, such as temperature (contact and non-contact), pressure, weight, level, flow rate, density, viscosity and particle size. Density, viscosity and particle size measurements are of special interest and are often linked to the control of sensory parameters.[72] This is important for the efficient production of food.

Downstream, during storage and distribution, there is a need to monitor temperature history, particularly in chilled and frozen food. There are various time-temperature indicator systems available which will show whether a critical temperature has been exceeded.

Immobilised enzyme biosensors allow an enzyme to produce products from an organic species that can be measured with an ion-selective electrode.[72] Initially used in the biomedical sector, biosensors have been developed for environmental monitoring, e.g. biological oxygen demand (BOD) and glucose depletion near the surface of meat, as a measure of microbial activity; a Defra LINK project aims to provide growers with a disposable biosensor using immobilised pyruvate oxidase that measures the sweetness and pungency of onions, replacing costly out-sourced pungency testing.[73]

Regulation: Additives and processing aids

Additives must be labelled on-pack, but processing aids are not required to be labelled. Whether a substance is an additive or a processing aid is therefore of critical importance given UK retailers and their suppliers' drives in recent years for 'clean labels', i.e. products to contain as few ingredients as possible.

EU food law has established positive lists of additives that may legally be added to food for a particular purpose, to the exclusion of all similar materials. These lists have largely been developed under Directive 89/107/EEC, the framework directive on food additives, which allows the use of food additives only if they perform a useful purpose, are safe and their use does not mislead the consumer. Approval therefore requires compilation and submission of a dossier of information to demonstrate these points. Approval of food additives currently requires approval from both Council and Parliament of a proposal from the European Commission (EC), which can take some time to complete.

Legislation proposed in 2006 aims to simplify and streamline the food additive, enzymes and flavourings approval system, allowing the EC to update and add to the EU positive list of food additives, following member state approval in the Standing Committee on the Food Chain and a right of scrutiny for the European Parliament. All approvals will be based on a safety evaluation carried out by the European Food Safety Authority (EFSA). The proposal also sets out a re-evaluation system for food additives currently on the EU market, based on risk assessments by EFSA.

For additives and flavourings, which are already covered by EU legislation, the proposals bring the rules into line with the latest scientific and technological developments and will improve the clarity of the legislation. However, issues raised with 343 *α, β*-unsaturated flavouring substances, out of a total list of 2,700 flavouring substances on the new positive list to be published later this year, will affect an estimated 75% of all flavourings used in food in the EU.

These substances, nearly all of which are naturally occurring in food, and have been used for decades in flavourings, may not be included. The over-zealous application of the precautionary principle (i.e. hazard-based, not risk-based assessments) will limit the use of these flavouring substances, not on safety grounds, but because of tenuous structural relationships with other known genotoxic substances.

The detailed controls made under 89/107/EEC are implemented into the national law of each EU Member State and stipulate:

- which food additives are permitted for use;
- their specific purity criteria; and
- conditions of use, including maximum levels for specific additives, some of which are set at *quantum satis*, i.e. in accordance with good manufacturing practice at a level not higher than is necessary to achieve the intended purpose.

In the UK, The Miscellaneous Food Additives Regulations 1995 (SI 3187), as amended, control the use of 25 classes of additives, including preservatives, which are defined as "any substance which prolongs the shelf-life of food by protecting it against deterioration caused by microorganisms".

6.3 Preservation

A better understanding of the complex chemical and biochemical interactions that can determine and affect the shelf-life of food materials and food products is needed.

Spoilage and deterioration of foodstuffs is a major contributor to food waste. Understanding how to preserve food so that it is ambient stable and nutritionally equivalent to fresh is a principal processing objective to support sustainability. This is particularly applicable in developing countries where damage by pests and microorganisms produces significant losses. This may include the control of environmental conditions supported by biosensor technology.

Improving the efficiency of high energy thermal processes (both cooling and heating) and the development of non-thermal processes to preserve food will have a significant positive effect on sustainability.

For example, refrigeration plants provide cooling or freezing of food, ranging from fresh produce (fruit and vegetables, meat and fish) to manufactured food. It is estimated that refrigeration systems use as much as 15% of the total energy consumed worldwide.[74] In the UK alone, there are between 1,500 to 2,000 food and drink manufacturing sites that are major users of refrigeration, accounting for over 4,500 GWh of electricity consumption. It is therefore necessary to find alternative refrigerants with specified refrigeration characteristics, continuously improve the efficiency of refrigeration systems (especially in terms of energy use), develop improved chilling techniques and support the objective of developing alternatives to high-energy thermal preservation systems.

Low energy shelf-life extension offers significant sustainability benefits and presents an important challenge to the chemical sciences, involving formulation, processing and packaging innovation.

Modified and controlled atmosphere packaging (MAP) is a method of maintaining the commercial shelf life of food. However MAP is only beneficial for food with a short shelf-life held under chilled conditions and this potentially conflicts with other drivers such as movement towards non-refrigerated storage of food. Other options include the development and application of in-pack devices, such as oxygen scavengers to maintain and extend shelf-life of processed food susceptible to oxidation.

Natural preservatives (such as phenolic diterpenes from rosemary) are known to exhibit antioxidant behaviour. The mode of action of these natural products needs to be validated before they can be applied, so further research is necessary.

Microbiological contamination is the most common cause of health problems for consumers and can be caused by poor hygiene at any stage in the food chain and by contamination of the water supply. Faster and cheaper microbiological tests for key pathogens are of paramount importance.

Food spoilage is caused by bacteria (not necessarily pathogens) and fungi (yeasts and moulds) which may secrete by-products that can be highly toxic. For example, the neurotoxin from *Clostridium botulinum,* and aflatoxins such as achratoxin A can be measured by using a range of methods including rapid EIA or ELISA methods.

6.4 Hygiene and food safety

Hygiene and food safety can be improved by the application of analytical chemistry, surface chemistry and chemical engineering to improve hygiene through all stages of processing. This includes disinfectants, non-aqueous cleaning methods and the use of novel materials for handling food.

Authenticity, control and better management of products, ingredients and mass flows through the food chain can be achieved by improvements to food analyses and diagnostics.

Re-evaluation of existing technologies such as irradiation technology, both gamma and electron beam, may provide a short term solution to improving food preservation, and consequently reducing food waste.

Foodborne illness is a significant cause of global ill-health arising from a range of pathogenic microorganisms. It is estimated that in England and Wales in 2000 the number of cases of foodborne illness was 1.34 million; there were 20,800 hospitalisations and 480 deaths.[75] In the EU campylobacteriosis remained the most frequently reported zoonotic disease in humans, with 175,561 reported confirmed cases in 2006.[76] In addition to zoonoses, physical, chemical and radiological contaminants can also pose risks to consumers.

In practice, testing for all the possible pathogens is expensive and time-consuming, so an indicator organism such as *Escherichia coli,* (present via mammalian faecal contamination), is usually targeted. Others tested in water include *Clostrida* spp., *Legionella* spp., *Salmonella* spp., *Pseudomonas* spp., *Streptococci* spp. and *Campylobacter* spp., all of which contain some pathogens.

A wide range of test kits is available for on-site use, involving adenosine triphosphate (ATP) assays, these are used as a hygiene monitoring or screening tools. Traditional (and slower) analyses, involving plate counting of incubated colonies are used as confirmation.

Critical food safety issues include those associated with raw materials that are a significant source of cross-contamination or illness when undercooked, and food-carrying preformed toxins, such as mycotoxin, which are significantly heat-resistant. These not only affect public health, but also contribute to food waste. There is a need for the further development of chemical-based decontamination systems for use once the crop has been harvested and processed. New methods will need to based on sensible risked-based analysis and not on hazard.

Given that 25-30% of food harvested is lost as a result of microbial and pest contamination, technologies such as irradiation, the process by which food is exposed to ionising radiation, present a method for the removal of bacterial pathogens and prevent spoilage of raw meat, seafood, prepared food and spices.

A statement released by the Joint Expert Committee on Food Irradiation, representing the World Health Organisation (WHO), concluded that irradiation up to 10 kGy causes no toxicological hazards and introduces no nutritional or microbiological problems.[77] Food irradiation remains a relatively unused technology in the UK, although it is approved for dried aromatic herbs, spices and vegetable seasoning. In 1997, the USA Food and Drug Administration approved irradiation for red meat, and consumer studies have shown that irradiated food marketed in many countries was judged superior to non-irradiated food, and has sold well.[78] However, in 2002 the European Parliament rejected a proposal to expand the list of foods that can be irradiated. The reason given by the European Commission was that of insufficient evidence proving safety.

Following the launch of the Food Standards Agency's farm-to-fork foodborne disease reduction strategy in 2001, there was a 19% reduction in foodborne illness by 2006.[79] Part of the FSA's strategy includes promotion of better food safety management and practice, and hygienic preparation of food commercially.

There are still gaps in knowledge and control over processing, including cleaning and disinfection, such as surface properties, microbial attachment and the forces required to clean surfaces effectively. In addition non-aqueous cleaning technologies are needed to control the contamination of food products from processing equipment and factory environments. All of these topics warrant further competitive research.

Regulation: biocide products

Biocides are defined in the EU Biocide Products Directive 98/8/EC, and cover 20 separate categories, including disinfectants, preservatives, non-agricultural pesticides for use against insects, slugs, snails, rodents, vertebrates, and antifouling products. Substances that are marketed and legally controlled as food additives are not covered. Since processing aids are defined in 89/107/EEC, they are excluded from the scope of biocide controls.

Only biocide products containing an active substance that has been approved under 98/8/EC are authorised for use. Existing products may, however, stay on the market until the active substances they contain have been approved. The directive provides for all existing active substances to be reviewed by May 2010, presenting significant restriction on the use of existing biocides and the development of new ones, although many play a vital role in minimising waste and assuring food safety.

In the UK, the use of chlorine as a processing aid in water to decontaminate poultry meat was successfully challenged by the EC, which argued that this use contravened EC Directive 92/116, on health problems affecting trade in fresh poultry meat. This directive requires the use of 'potable water' for most purposes, and the use of chlorine rendered the water non-potable. Since May 2001, chlorine has no longer been able to be used for this purpose. This is despite chlorine being the most effective method of minimising in fresh poultry meat the presence of *Campylobacteria*, the most prevalent cause of foodborne illness in the UK.

There are currently no substances approved by the EC under Regulation 853/2004 (specific rules for hygiene for food of animal origin) to remove surface contamination from products of animal origin. In addition, the hygiene requirements for fishery products set out in the regulation make it clear that (whether on land or at sea) only potable water (or, where appropriate, clean water) may be used to wash fish. This means that processing aids may not be used in contact with fish, although waste reduction and food safety assurance could be benefits of such treatments.

The general food hygiene Regulation (852/2004) controls the hygienic production of products of non-animal origin and requires the use of potable water. However, the FSA has advised that, as the EC took legal action against the UK only in respect of poultry meat, other uses of chlorine as a processing aid can continue to be regarded as lawful.

For decontamination of produce, the biocide products category in question is Type 1: "Human hygiene biocide products", which includes products added to water to wash produce for public hygiene, although not to protect it against plant pathogens (which are subject to separate EU rules on plant protection products). Whether a wash water chemical is an additive or processing aid is of great importance, since it is unlikely that the UK consumer will accept a 'natural' agricultural product (such as leafy salad) which carries the name of a chemical additive on the label. Therefore, in practice, wash water decontaminants must be able to be classed as processing aids, which requires their having no lasting technological effect on the produce, a key challenge for the chemical sciences.

6.4.1 Contamination

Contaminants are substances that have not been intentionally added to food. These substances may be present in food as a result of the various stages of its production, packaging, transport or holding. They also might result from environmental contamination.

Screening and sensor systems are necessary to support rapid diagnostic tools throughout food processing and manufacture. The potential application of screening and diagnostics for improved food safety has a very wide scope. Some of the areas include detection of heavy metal contamination, toxicity screening, allergen testing, pesticide residues, microbial contamination and detection of disinfectants and disinfectant by-products. With a large number of potential pollutants, a variety of analytical methods is required to measure the level of natural and man-made chemicals in the environment, potentially at high concentrations (percent levels) and at very low levels (parts per trillion).

Increasing population and environmental pollution will produce new hazards. It is important to monitor and manage the status of soil and water since each have an impact on both animal (human) and environmental health. For example, marine food, whether harvested or farmed, will become more important. Plankton are critical food for filter-feeding shellfish and the larvae of commercially important crustaceans and finfish. Evidence is increasing that "cultural eutrophication" from domestic, industrial and agricultural wastes can stimulate harmful algal blooms. It is even possible that algal species which are not toxic may be rendered so when exposed to atypical nutrient regimes. These can find their way through levels of the food chain and are ultimately consumed by humans causing a variety of gastrointestinal and neurological illnesses.[80] Detection and quantification of such biotoxins involves bioassays using rodents. These methods are being replaced by chemical methods such as liquid chromatography mass spectrometry (LC-MS), enzyme-linked immunosorbent assays (ELISAs) and functional assays but this work needs to be increased, by international production of validated methods and standard reference materials.

Monitoring water quality for inorganic materials is performed using ion chromatography (IC), ion coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) and for organic materials, gas chromatography mass spectrometry (GC-MS), gas chromatography flame ionisation detection (GC-FID), LC-MS and high pressure liquid chromatography (HPLC). Portable field testing kits for specific analytes, based on immunochemical methods can also be used both for water, and to measure the nutrient content of soils, enabling the optimum application of fertilisers. In-situ sensors that can measure the mineral and organic content of water continuously, thereby revealing fluctuations that might otherwise be missed by periodic spot sampling and off-site analysis, are being regularly used by water companies in the developed world.

6.4.2 Packaging

The use of intelligent packaging systems and technologies for the improved control of food spoilage, hygiene and food safety is a key area for further development, the emphasis being on control rather than detection. For example, there has been considerable work on developing the use of time temperature indicators, but their uptake has been limited, since detection without remedy, produces more waste.

Nanotechnology has potential benefits by reducing deterioration. For example, packaging based on nanotechnology that absorbs oxygen will have significant benefits on the shelf-life and eating quality of certain foods. However, such approaches cannot be applied without fully considering the microbiological impact of reducing oxygen, which may include stimulation of growth or selection for wholly or facultative anaerobic pathogens such as *Clostridium botulinum*.

Nanoscale film on confectionery, based on oxides of silicon or titanium with antimicrobial properties could increase the life of much manufactured food. Currently the application of such materials to food with a short shelf-life is limited by the long contact time needed to achieve the desired microbial effects. Additionally, the effect of such film may be limited to the portion of the food that is in direct contact with it.

Nanolaminates for food packaging include edible films for fruit, vegetables, meat, and chocolate baked goods. Films that provide specific protection from moisture, lipids and gases can improve the textural properties of food, and serve as carriers of colours, flavours, antioxidants, nutrients, anti-browning agents, enzymes and antimicrobials.

Nanoparticles could be used in printing ink, changing the colour of the label to indicate the remaining shelf-life of a perishable food, possibly replacing (with regulatory agreement) the current 'use-by date' labelling system.

These developments require significant technical, legal and consumer education issues to be considered.

6.5 Chemical science applications

Technologies applicable to food processing and manufacturing can be found in the following table. This table also identifies the underlying science and technology disciplines necessary to develop these research areas. A multidisciplinary and interdisciplinary approach is essential, with input identified from organic, inorganic, physical and analytical chemistry, structural biology, biochemistry, medicinal chemistry and food science, materials and polymer chemistry and chemical engineering.

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of novel in-line chemical sensors for improved process control by optimising conditions and inputs during food processing, and chemical addition during effluent treatment.				✓			✓
Analysis of the composition of composts, digestates and waste biomass to monitor quality, to verify and validate processes and to assist with certification.				✓			
Development of micro-sensors in food packaging to measure food quality, safety, ripeness and authenticity and to indicate when the 'best before' or 'use-by' date has been reached; for example, using biodegradable ink.				✓			
Harnessing of analytical chemistry to design rapid, real-time screening methods, microanalytical techniques and other advanced detection systems to screen for chemicals, toxins, veterinary medicines, growth hormones and microbial contamination of food products and their raw materials. To detect that they are not contaminated at source or during distribution, storage and processing, and that they contain required nutrients and are safe and fit for purpose, thereby avoiding their (re)processing, transportation or recall, and avoiding waste.	✓	✓	✓	✓		✓	
DNA analysis for animal genotyping to establish breed quality and authenticity.				✓	✓		
Research into naturally occurring carcinogens in food such as acrylamide and mutagenic compounds formed in cooking.	✓			✓			
Development of rapid sensors, such as ELISA, for detection of allergens in food materials and on food contact surfaces.				✓			
Efficacy testing and food safety of new food additives, such as natural preservatives and antioxidants.				✓			
Methods for the detection of disinfectants and disinfectant by-products, a better understanding of the mechanisms involved in the formation of disinfectant by-products, and determination of the efficacy of disinfectants against different microorganisms that will improve food safety and hygiene.	✓			✓	✓		
Use of analytical methods to support life cycle analyses of the environmental impact of individual food products, packaging and materials.				✓			
Extraction and application of valuable ingredients from food waste, e.g. enzymes, hormones, phytochemicals, probiotics and chitin.	✓	✓			✓	✓	✓

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Polymer chemistry to develop new biodegradable, recyclable or multifunctional packaging materials, to reduce environmental damage and the quantity of packaging used in the supply-chain.						✓	
New cleaning materials and disinfectants with lower toxicity to remove surface fouling in food processing and waste treatment.	✓	✓		✓			
A better understanding of naturally-occurring chemicals and the use of these in the supply chain: new antimicrobials, natural disinfectants, antioxidants, colours, flavour chemicals, salt replacers, emulsifiers, encapsulating agents, preservatives.	✓	✓	✓	✓	✓	✓	✓
Development of safe fat-replacers that produce the mouth feel of fat and deliver the same satiety signals after consumption.	✓			✓	✓		
Understanding the metabolomics of spoilage of crops and food, to reduce losses.					✓		
Research into the relationship between flavour chemicals and flavour perception to enhance understanding of the chemical signals that stimulate the senses during eating, that will help to improve the consumer acceptance of food and reduce losses.	✓			✓	✓		
Understanding the chemical transformations taking place during processing, cooking and fermentation processes, that will help to maintain and improve palatability and acceptance of food products by the consumer.	✓			✓	✓		
Identification and application of novel enzyme chemistry for modifying ingredients, such as proteins.	✓				✓		
The development of chemical treatments to remove pathogens from raw ready-to-eat crops without affecting eating quality or nutritional content.	✓			✓			
In aquaculture, improvement of reproductive success, shelf-life of the finished product and resistance to disease; development of favourable behavioural traits and built-in osmoregulation; development of a high-yielding omega-3 soya bean to replace industrial fish feed and reduce industrial fishing.	✓				✓		
Methods for the synthesis of food additives and processing aides.	✓				✓		
Chemical stabilisation technologies for produce and their formation and delivery.			✓	✓			✓
Development of new non-animal meat substitutes and analogues with improved texture and flavour.					✓		

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Greater understanding of the biochemistry of filamentous fungi to help to identify new methods for the control of mycotoxins and the contamination of human and animal food products.				✓	✓		
Development of bacteriophages and bacteriocins with antibacterial activity against foodborne pathogens and spoilage by microorganisms.				✓	✓		
Application of food metabolomics to the quality and safety of food – molecular profiling of food products to generate more comprehensive molecular descriptions of biological systems using analytical biochemistry techniques.					✓		
Technology to produce sugar replacers and natural low calorie sweeteners to improve nutrition and combat obesity.	✓				✓		
Use of plants and microorganisms as factories for new food ingredients.					✓		
Understanding the life-stage nutritional requirements of humans, livestock and fish.				✓	✓		
Development of artificial digestion system for researching digestion of new food and ingredients.					✓		
Further development and understanding of fortified and functional food with specific health benefits.					✓		
Development of more efficient crop drying technologies, especially in tropical countries, which do not contaminate raw materials.							✓
Improved understanding of algae aquaculture technology to produce new human and animal food and high-value food ingredients, such as beta-carotene.	✓				✓		✓
Further development of the biorefinery concept, to make maximum use of raw materials and by- and co-products, by making a range of products at a single site and maximising energy efficiency.							✓
Use of mass, heat and energy transfer principles, combined with advanced data handling, to minimise losses of product, water and energy throughout the supply-chain.							✓
Intensification of food production processes by scaling down and combining process steps.							✓
Development of improved routes for by- and co-product processing to reduce waste and recover value.							✓
Development of milder extraction and separation technologies with lower energy requirements.							✓

Application (Underpinning science & technology →)	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Increased efficiency of refrigeration technology at all stages in the supply-chain, e.g. super chilling as an alternative to freezing.			✓				✓
Development of ambient storage technologies for fresh produce that avoids the need for chill and frozen storage, saving the considerable costs involved in cold storage.			✓				✓
Development of improved food preservation methods for liquids and solids, including rapid chilling and heating, and salting.			✓				
Development of technologies to minimise energy input at all stages of production, e.g. high pressure processing and pulsed electric fields.							✓
Development of self-cleaning surfaces and robotic food production techniques to eliminate contamination during changeover and improve manufacturing hygiene.			✓			✓	
Development of greater understanding of, and thereby control of, the effects of processing on food structure and texture, to ensure that food remains wholesome and to reduce waste.			✓				
Improvement in the heat stability of foils.			✓				
Use of cellulose as a food structuring agent.			✓		✓		
Effects of pH and salt on protein denaturation, to preserve food quality.			✓		✓		
Optimisation of forces needed to clean surfaces during food processing, to minimise energy requirements.			✓				✓
Development of processes and systems improving the recyclability of plastics, glass and cardboard, for example by enhancing the properties of recycled cellulose fibres.						✓	✓
Development of lightweight packaging to minimise raw material consumption and waste, e.g. glass bottles and corrugated cardboard.						✓	
Development of single-layer meat packaging to replace the multilayer packs containing gas impermeable, water resistant and rigid layers.						✓	
Use of CO_2 as a feedstock for packaging material, for example the production of a novel biodegradable plastic material made from epoxides and CO_2.						✓	
Development of smart packaging capable of absorbing oxygen to preserve the freshness and shelf-life of food (with food safety caveats requiring assessment in relation to anaerobic pathogens).				✓		✓	
Development of improved, more cost effective fouling-resistant materials for use as membranes in food processing and effluent treatment.						✓	✓

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Application of acid-sensitive alginates or plasma gels that slow down the emptying of the stomach and give a 'slow energy-burn' to combat obesity and over-consumption.			✓		✓		
Application of hydrophobins (low molecular weight proteins from fungi) to produce stable air-filled emulsions that can reduce fat content in emulsion-based food, e.g. mayonnaise.			✓				
Development of the encapsulation of food to protect against environmental factors.						✓	
Application of nanofiltration to enhance food safety by filtering out microbes from food, or removing lactose from milk for replacement by alternative sugars.						✓	✓
Development of nanoscale biosensors in food, e.g. detection of food pathogens and toxins.				✓	✓	✓	
Development of functional (i.e. antimicrobial) and intelligent packaging such as nanolaminates, including edible films, films providing specific protection from moisture, and lipids improving texture and acting as carriers for various components (such as flavours and antioxidants).			✓			✓	
Using metabolites to help understand the flavour and taste of food.						✓	

7 Distribution and retail

Distribution is the process by which food products move from their point of manufacture or supply to their point of sale. By their very nature these processes inevitably contribute to the overall carbon footprint of products, a footprint that gets larger as the distribution chain lengthens. The Wise Moves project[81] investigated the various stages in the food supply chain where greenhouse gas emissions are generated, and concluded that a lower carbon food system would have the following features:

- use of indigenous and seasonal produce, in preference to foreign food or food imported out of season;
- 'local clustering', inputs to a product would be situated near to the site of production;
- efficient operation and management of processing plant;
- least use of temperature-controlled storage (where compatible with food safety standards);
- minimal distance from point of production to point of consumption; and
- logistical efficiency (fuel efficiency, consolidation of loads, loading vehicles as full as possible).

7.1 Scale and influence of the retailer

Retailers need to recognise and take advantage of their unique position to implement a successful approach to sustainability. The UK supermarket sector has a reputation for introducing innovation in the food sector and, by its size, can and should champion sustainability in the UK and worldwide. For example, 'own brand' products give supermarkets influence back along the supply chain. They can engage with primary agriculture, food processing and manufacture, to ensure food safety and traceability, in addition to reduce waste in product and package.

Retailers need to ensure they commit sufficient resource and expertise to sustainability. This applies particularly to understanding of the various technologies involved, which would not necessarily feature in traditional retailer-supplier technical relationships.

Food is distributed to and retailed from many outlets, from garage forecourts to corner stores; local outlets play a vital role ensuring food gets to the less mobile or more elderly consumer. However, supermarkets dominate the UK retail market in food, representing 56% of all retail food sales in 2007, estimated to be worth £72,800m, an increase of 18.5% since 2002.[82] The four largest supermarkets, Tesco, Asda (part of the global Wal-Mart Group), Sainsbury's and Morrisons account for 76.3% of the total UK Grocery market. Tesco is the largest food retailer in the UK with a 31.4% share. The growth and success of the large UK supermarket groups has been dominated by the development of retailer 'own-label brands' which accounted for roughly 20% of sales (worth £10,200m) in 2000, and nearly 40% by 2004.[83, 84]

While the supermarkets have had to be responsive to consumers' conventional needs and expectations (price, choice, availability, convenience, quality, and health), the wider issues of ethical trading, animal welfare, environmental impact and sustainability have become increasingly important. In particular, sustainability of food has gained a high profile and become politically sensitive within the UK. Sustainability, therefore, together with social, environmental and other ethical concerns, has risen up the corporate agenda and now directs policies towards the supermarket groups becoming business 'pillars and drivers'.

For example, Marks & Spencer's 'Plan A', which covers sustainability of raw materials, as well as environmental, ethical and nutritional considerations, is an example of how the sector is beginning to develop strategic plans and business approaches for sustainability, with a high degree of transparency.[85] Another good example of collaboration and innovation amongst retailers is Sedex, a web-based data sharing system for managing ethical information (labour standards, environmental management and practices) throughout global supply chains. This system was initially championed and established through collaboration and co-operation between retailers and manufactures.[71]

Retailers need to recognise and take advantage of their unique position to implement a successful approach to sustainability. Having 'own brand' food products gives supermarkets a great deal of influence along the whole supply-chain. They can engage with primary agriculture, and food processing and manufacture, to reduce waste in product and package, improve standards of food safety and traceability, and drive innovation in new product development. Due to the scale of operations in the UK supermarket sector, apparent small changes within their businesses can have a large effect in a relatively short time.

- Packaging presents obvious, visible questions of sustainability (see Chapter 6). The quest for new materials, systems and technologies will continue to require the application of the chemical sciences.
- Food safety within the manufacturing sector has always been a primary consideration, and retailers have an excellent record. Food safety continues to provide the chemical sciences with opportunities, especially in thermal processes and controls, and in disinfection and the use of antimicrobial surfaces.
- Retailers have been at the forefront of the application of analytical techniques to support their own internal surveillance activities and those of their suppliers. Examples include analysis of pesticide residues, irradiation, genetic modification, adulteration, allergens and traceability.
- The demand for healthier food (see Chapter 8) is stimulating new product development, with reduction of salt, sugar, fat and saturated fat in own brand products. Innovation in the area of functional health-foods is desirable for retailers to differentiate their own brand products from the competition, thus retailers have started to invest in research by funding external expert bodies and institutions. The chemistry of analysis and diagnostics has a central role in establishing data for labelling and claims.

7.2 Transport

In addition to adopting regional distribution centres (RDCs) as hubs for distribution, road haulage must reduce carbon emissions, including the use of fuel with a low carbon footprint, and the minimisation of unnecessary transport miles.

Research on food miles showed that the transport of UK domestic food in 2002 accounted for 82% of vehicle kilometres attributable to the supply chain, the balance arising overseas.[86] Of this, 24% was by light goods vehicle (LGV), 22% by heavy goods vehicle (HGVs) and 54% by cars used on shopping trips. In terms of carbon emissions (10 Mt of carbon, 1.8% of the UK annual total), 15% was from LGVs, 62% from HGVs and 23% from cars. Air miles comprise approximately 1% of food tonnes per kilometre, although this form of transport has the highest environmental impact per tonne. While there was a rapid growth in air freighted food during the 1990s, this has now levelled off.[87]

It is suggested that shorter supply chains through local sourcing can cut transport emissions considerably, provided the chain remains logistically efficient. In addition to adopting regional distribution centres (RDCs) as hubs for distribution, road hauliers must reduce carbon emissions by adopting fuel with a low carbon footprint, and minimising unnecessary transport miles.

The need for intelligent transport systems is critical, with the emphasis on improving efficiency. In June 2008, 37 of the UK's leading food and consumer goods companies announced a major transport collaboration that will significantly reduce the environmental impact of food distribution in the UK. The initiative includes sharing vehicles and more efficient warehousing. It is anticipated to save 48 million miles of travel by the end of 2008 alone and conserve 23 million litres of diesel fuel per year.[88] Retailers are also beginning to transport produce by sea instead of by airfreight, and they are running pilot schemes to switch freight from road to rail.

Maximal loading of vehicles can be achieved through a range of initiatives, including improved packing, investment in double-decker trailers, and using suppliers' vehicles to deliver to shops on their return trips. Cross docking is also having a positive effect. Increasing affordability may see wider application of radio frequency (RF) tagging of products, packaging, pallets etc., which offers improved logistics efficiency.

The biggest opportunity for the chemical sciences in addressing this issue lies in further research towards sustainable and efficient transport by developing improved catalysts, lubricants and fuel formulations, new energy storage systems and energy efficient vehicles.

7.3 Energy use and process engineering

Reduced energy usage per unit of distribution centre and retail space through state-of-the-art low-carbon technologies, renewable energy generation and energy-efficient practices is necessary. For example, a major opportunity for the chemical sciences in the area of refrigeration is to achieve improved energy efficiency and the development of replacement refrigerants. Application of trigeneration and combined heat and power technology (CHP) technology for stores and distribution centres.

Improving sustainability in retail stores is directed towards reduced use of energy, better management of waste, and increased recycling. Waste is being addressed by the development of aerobic digestion and gasification to divert food waste away from landfill and to generate energy (see Chapter 9). Retailers have set targets to reduce the carbon footprint of existing stores and are designing new stores with a significantly lower footprint. They are developing energy-efficient stores to test out low-carbon technologies as models for the future. For example at the Tesco store in Bangkok, solar panels the area of three football pitches cover more than half of the roof. These provide 12.5% of the store's energy consumption and save 400 tonnes of carbon dioxide. It is the largest rooftop solar energy system in the region.

Reducing energy use per unit area of distribution centres and retail space will involve state of the art low-carbon technologies, renewable energy generation and energy-efficient practices. For example a major opportunity for the chemical sciences is refrigeration. Retailers are high users of energy for refrigeration, ahead of catering and refrigerated transport. Improving the efficiency of refrigeration systems and finding alternatives to hydrofluorocarbons (HFCs) is a high priority for the retail sector. Refrigerants to replace HFCs include carbon dioxide for larger fridges, freezers and air conditioning units. A new technology, the transcritical carbon dioxide heat-pump, is being used for commercial refrigeration. It can provide refrigeration at temperatures below 0 °C, and simultaneously use the waste heat to produce hot water at temperatures up to 90 °C. This can reduce greenhouse gas emissions by about 25% compared with conventional separate heating and refrigeration systems. Transcritical carbon dioxide could provide sufficient hot energy to provide all the heating for the supermarket and power additional cooling with an absorption system.[89] A fundamental technological breakthrough is finding other formats, particularly ambient storage, that provide the product advantages such as flavour, texture, and colour of chilled storage but with lower consumption of energy.

Trigeneration (the simultaneous production of mechanical power, heat and cooling from a single heat source) and combined heat and power technology (CHP) for stores and distribution centres should be more widely harnessed. These approaches allow the capture and reuse of heat created through power generation to reduce the overall footprint. Retailers have been active in developing a range of management and technical systems for application in primary agriculture. These include assurance schemes based on welfare and environmental standards, and integrated farm management. They affect directly the responsible use of energy, water and natural resources. An example can be found in the horticultural sector, where suppliers of tomatoes use CHP to heat greenhouses and send excess energy to the National Grid.[90] Carbon dioxide is recycled in the greenhouses and absorbed by the crop, reducing carbon dioxide emissions and improving the tomatoes.

7.4 Lifecycle analysis

A detailed and structured approach to the carbon footprint of a product over its lifecycle will provide a management tool for improvement, and a communication route to relate improved sustainable practices to consumers. The methodology for carbon mapping of products should be developed as part of a collaborative initiative, between all sectors of the food chain and public bodies.

While it is suggested that shorter supply chains through local sourcing can cut transport emissions considerably, it is also recognised that the advantages of reducing mileage need to be balanced against possible increases in other emissions across the product lifecycle. Basing measures on food-miles alone ignores the impact of the supply chain as a whole. It may, for example, be less damaging to the environment to import tomatoes from Spain than to grow them under protected, relatively energy-intensive conditions in the UK. All inputs must be considered to identify their contribution to overall environmental impact. Lifecycle analysis shows that local food does not offer complete resolution of all the environmental challenges posed by current production and distribution practice.[91] Lifecycle analysis is therefore essential for substantiating the effect of proposed approaches, and ensuring that the best course of action is taken. It is therefore relevant to the entire food chain, since the best solutions will require the co-operation of growers, manufacturers and distributors.

Retailers are now involved in measuring the carbon footprint for their own brand products, based on lifecycle analysis. Initial studies by retailers on a number of products have used The Carbon Trust's draft standard to track the impact of food processes.[92] This 'carbon mapping' technique may develop into a yardstick of sustainability, and be used to establish benchmarks in the future. However, the methodology proposed is complex, time-consuming and costly, and this may restrict its potential uptake. Carbon labelling also needs to provide meaningful information to consumers, which it cannot easily do if a food can either be stored chilled or frozen, or requires heating or cooking. Each process applied by the end-user greatly affects the overall carbon footprint of an individual product, and this needs to be communicated in a meaningful way.

Despite this, it seems likely that pack declarations of carbon footprints will, at some stage, become a competitive feature and will put pressure on retailers to make improvements. However, carbon footprints of entire businesses and supply chains would bring greater systemic benefits, which in turn would require an increased focus on the use of technology and the chemical sciences. It is conceivable that sustainability may become a measure of a supplier's performance. Methodology for carbon mapping of products should be developed as part of a collaborative initiative.

7.5 Chemical science applications

Technologies applicable to the distribution and retail sector can be found in the following table. This table also identifies the underlying science and technology disciplines necessary to develop these research areas. A multidisciplinary and interdisciplinary approach is essential, with input identified from organic, inorganic, physical and analytical chemistry, structural biology, biochemistry, medicinal chemistry and food science, materials and polymer chemistry and chemical engineering.

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of micro-sensors in food packaging to measure food quality, safety, ripeness and authenticity and to indicate when the 'best before' or 'use-by' date has been reached; for example, using biodegradable ink.				✓			
Design of rapid screening real-time analytical methods, microanalytical techniques and other advanced detection systems to screen for chemicals in crops and food products, to improve safety and reduce waste through transporting contaminated food, e.g. antibiotics and growth hormones in meat and toxins in food.				✓			
DNA analysis for animal genotyping to establish breed quality and authenticity.				✓	✓		

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of rapid sensors, such as ELISA, for detection of allergens in food materials and on food contact surfaces.				✓			
Efficacy testing and food safety of new food additives, such as natural preservatives and antioxidants.				✓			
Use of mass, heat and energy transfer principles, combined with advanced data handling, to minimise losses of product, water and energy throughout the supply-chain.							✓
Development of processes and systems improving the recyclability of plastics, glass and cardboard, for example by enhancing the properties of recycled cellulose fibres.						✓	✓
Development of lightweight packaging to minimise raw material consumption and waste, e.g. glass bottles and corrugated cardboard.						✓	
Development of single-layer meat packaging to replace the multilayer packs containing gas impermeable, water resistant and rigid layers.						✓	
Development of biodegradable, flexible films for food packaging, e.g. corn starch, polylactic acid or cellulose feedstock, able to withstand the chill-chain, consumer handling, storage and final use (e.g. microwave or conventional oven).						✓	
Use of CO_2 as a feedstock for packaging material, for example the production of a novel biodegradable plastic material made from epoxides and CO_2.						✓	
Development of smart packaging capable of absorbing oxygen to preserve the freshness and shelf-life of food (with food safety caveats requiring assessment in relation to anaerobic pathogens).				✓		✓	
Construction of super insulators.			✓				
Development of functional (i.e. antimicrobial) and intelligent packaging such as nanolaminates, including edible films, films providing specific protection from moisture, and lipids improving texture and acting as carriers for various components (such as flavours and antioxidants).			✓			✓	

8 Consumer

There are three pressing issues for the future. The first relates to the problem of supply of food for the hungry, the second to maintaining the security of the food supply to those with enough, and the third to the development of food ingredients and products that positively enhance the long term health and wellbeing of consumers. In addition to this, consumer attitudes towards science and technology in the food industry must be taken into account.

8.1 Supply for the hungry

The transfer of existing and new technologies to the developing world is of huge importance in order to achieve the necessary increase in food supply for these regions.

The first United Nations Millennium Development Goal (MDG), set in 2000, is to 'eradicate extreme hunger and poverty'.[93] To achieve this, the target is to halve by 2015 both the number of people suffering from hunger and those whose income is less than one dollar a day. A major challenge that is still unrecognised is the one referred to as hidden hunger, generated by poor dietary quality and involving inadequate micronutrient intake. Implementing appropriate intervention strategies for specific populations is the only way in which the Millennium Development Goals have any chance of being achieved.

Under-nutrition remains a major cause of mortality for children throughout the world, with around 10 million children dying before the age of five years. Although global childhood mortality declined from 147 deaths per 1,000 live births in 1970 to 80 deaths in 2002, improvements are not universal. In some regions, especially in sub-Saharan Africa, childhood mortality has not decreased, and 14 African countries have child mortality rates higher now than in 1990.[94]

Food sustainability needs to consider the effects of malnutrition throughout the world. The first Millennium Development Goal uses the prevalence of underweight in children under five as a key indicator. Underweight measures chronic malnutrition (low height for age, or stunting) as well as acute malnutrition (low weight for age, or wasting), but the contribution of stunting to underweight is greater than that of wasting.

Stunting is generally declining worldwide. The World Health Organisation (WHO) reported that between 1990 and 2000 the global prevalence of stunting in children fell from 34% to 29.[95] Stunting is defined by the WHO as two standard deviations below the mean for height and age. Children who are underweight or stunted in growth may not show catch up growth in later childhood, and so carry the risk of continuing poor health into adult life.[96] In some populations such as South Africa, children who are growth stunted co-exist with those who are overweight or obese.[97]

8.1.1 Food security

Climate change, competition for land use, and population and economic growth are contributing to consumer uncertainty about food security. As discussed previously, the world's population is expected to increase to over nine billion by 2050. This, together with the new affluence of emerging middle classes in India and China, presents a challenge to sustain food production and secure supply for all into the future.

A co-ordinated approach using science and technology is required to ameliorate risks to supply, and to increase production efficiency for all stages of the food supply chain. The demands placed on the environment must be taken into account: use of land, sea and air; use of water and energy; and even the generation of waste must be sustainable to secure a lasting supply of food. Several technologies can play a role in ensuring there is enough food and energy for basic needs. These have all been covered in other sections of the report:

- improved crop varieties (Chapter 5);
- disease control (Chapter 5);
- soil science (Chapter 5);
- packaging and storage technologies to ensure there are raw materials for either direct consumption or further processing (Chapter 6);
- food processing technology to preserve food (Chapter 6); and
- fabricated food, e.g. meat and fish substitutes (Chapter 6).

8.2 Health and wellbeing

Research into nutrigenomics, to identify requirements for different demographic groups and tailored diets for individuals, should be supported, and the chemical sciences should be promoted to develop food that meets these requirements.

The understanding and control of fat chemistry should be extended, further developed and promoted to bring about reductions in trans fatty acids (TFAs), building on successes in the UK.

Research into the chemistry of fundamental food transformations should be undertaken with a view to creating products with a low glycaemic index (GI) by novel heating processes to minimise the gelatinisation of starch, and the use of other soluble and insoluble fibres whilst maintaining good sensory qualities.

Research into the chemistry of encapsulation should be promoted. Physical and organoleptic properties of encapsulating materials should be characterised, and also their bioavailability. Ideally, naturally-derived encapsulants are required to extend the potential of this technology.

Whilst food scarcity is a problem in the undeveloped world, the developed world sees issues arising that relate more to excess production and consumption.

Cancer and cardiovascular disease, including heart disease and stroke, are the major causes of death in England, accounting together for almost 60% of premature deaths. It has been known for a long time that poor diet contributes to cardiovascular disease,[98] but it has only more recently been acknowledged that about one third of cancers can be attributed to poor diet and nutrition.[99]

Over-nutrition and reduced physical activity have contributed to the growth of obesity. The most recently released results from the Health Survey for England show that, using BMI as a definition of total obesity, 24% of men and women in England are now obese, a trebling since the 1980s, and 65% of men and 56% of women (24 million adults) are either overweight or obese. Men and women were equally likely to be obese; however 3% of women are morbidly obese compared to 1% of men. Obesity is an increasing problem in children and young people, 16% of 2-15 year-olds are now obese.[100] Obesity brings its own health problems, including hypertension, heart disease and Type II diabetes; and obesity is responsible for an estimated 9,000 premature deaths per year in England. It is estimated that the treatment of ill-health from poor diet costs the National Health Service (NHS) at least £4,000m each year.

Under-nutrition is also a problem in the developed world; the increase in the elderly population, whose mastication and digestive processes are compromised, is leading to malnutrition.

The recent cross-government strategy for England includes the UK Government's healthy food code of practice, which aims to increase the availability of 'healthier food', including continued reduction in the levels of salt, sugars and saturated fat in prepared and processed food and drink.[101]

Diet in the UK and Europe has become based on more convenient and more processed products i.e. the fast food culture.[102, 103] Products consumed now are therefore softer; they empty from the stomach more quickly than natural foods and the macronutrients are available more readily and faster than from non-processed foods. This in turn leads to the stomach feeling empty sooner and a demand for calories being delivered to the body well before the next meal time. The consumer therefore may eat more, as well as snacks between meals.

8.2.1 Fats

For many years, the 'diet and health' spotlight has been on fats, with special emphasis on the message that not all fats are equal in terms of how they affect health.[98] In terms of making changes to the food supply, the focus has been on trans fatty acids (TFAs). TFAs can be formed during hydrogenation, the process of converting liquid oil into solid fat. Like saturated fatty acids (SFAs), TFAs raise LDL cholesterol levels in the blood, thereby increasing the risk of coronary heart disease (CHD). The World Health Organisation (WHO) and organisations including the UK Food Standards Agency (FSA), and the European Food Safety Authority (EFSA), recommend that manufacturers should reduce the levels of TFAs arising from hydrogenation; and note the progress that industry has made in that direction. Consumption in the UK has been declining, with products previously containing hydrogenated vegetable oils subject to reformulation.[104] The consensus from a number of authoritative bodies is that, although the risk to health of TFA intake at average consumption levels is small, the intake should not be increased.

Reduction of TFAs and SFAs brings technical challenges. For example, the need to reduce saturated fats requires alternative sources of structuring agents to replace fat crystals; these may be from natural sources (waxes) or synthetic (such as sugar polyesters). Reduction in crystal content gives softer products, with a lower melting temperature, reducing storage stability. Fat reduction or even fat replacement have worked to an extent, through careful study of the structural role played by fat in products, and the replacement of the physico-chemical stimuli delivered, with other structural forms, such as polymer-thickened aqueous solutions. However, there is scope for further research, particularly where fat performs as a water barrier or carrier of taste and flavour components that are only soluble in oil. Furthermore, we do not completely understand the manner in which fats and oil produce the lubrication necessary for bolus formation and swallowing.

Within the group of polyunsaturated fatty acids (PUFAs), it is important to have a sufficient supply of the omega-3 series. Since they cannot be metabolically synthesised by humans, they can be considered comparable to vitamins. Omega-3 fatty acids, or the triglycerides containing them, can be incorporated into food products; however they must be added close to the end of the manufacturing process because high temperatures and heavy metal ions cause rapid oxidation. Another technique to protect these fats from oxidation in prepared foods is microencapsulation. This technology is already available, but the formation of nanoemulsions provides further potential.[105]

Mostly recovered from fish, there is a need for new sources of omega-3 fatty acids. Extraction from marine algae is a possibility. Most essential fatty acids (EFAs) are extremely sensitive to heat, light and oxygen, and go rancid very quickly. This not only affects flavour, but could also cause damage to health by increasing free radical formation in the body. One technique to prevent oxidation is the addition of antioxidants to the product. However, the chemistry of oxidation needs further investigation and control. Natural structures achieve stability by segregating reactants, and this should be possible in fabricated foods.

The obvious challenge to food sustainability is to produce food that reduces the fat and sugar components having harmful properties, while maintaining the consumers' perception and satisfaction of the product. For example, food material texture/microstructure has a significant influence on the sensation of satiety and on various aspects of health; these effects arise through the influence of the microstructure on the rate of breakdown in the GI tract. By designing the microstructures of food biopolymer systems it is possible to achieve the slower breakdown of food material. This can lead to a greater sensation of satiety, through the mechanical properties of the material in the gut. Also the microstructure and bulk properties of food products can influence the rate of uptake, into the body, of nutrients or other ingredients.[106]

In order to improve our ability to formulate foods with improved functionality in these areas, and to create model systems that will allow us to understand better the mechanisms by which these benefits arise, considerable research has been conducted to create food materials based on biopolymer gel materials with controlled microstructures.[107, 108] The advantage of this approach is that food materials can be produced from similar or identical ingredients that have very different textures, simply through control of the process conditions under which they are produced.[109] As a consequence of these investigations into the design of functional foods, it is increasingly important to develop in vivo approaches or techniques for evaluating their behavior in the digestive tract, such as magnetic resonance imaging (MRI).

8.2.2 Carbohydrates

More recently, the spotlight has been on the important role of carbohydrates in food, namely how their structure and functional properties (carbohydrate quality) can also influence health outcomes. [110]

A recent simple classification of carbohydrates is that proposed by Englyst:[111]

- glycaemic carbohydrates, which are digested and absorbed in the small intestine; and
- non-glycaemic carbohydrates, which enter the large intestine.

Those causing a large rise in blood glucose are said to have a high glycaemic index (GI). Glycaemic carbohydrates are available carbohydrates, which have been sub-classified according to their sugar type, their degree of polymerisation and their likely rate of digestion in the small intestine.[111] There is now a large body of evidence that a low glycaemic diet has health enhancing benefits. This evidence comes from a meta-analysis of the epidemiological evidence and also the intervention trials that have been carried out with diet of varying GI.[112]

Many foods can be reformulated to avoid high GI, but the sensory quality during eating must be maintained, and requires a better understanding of texture and flavour release from these novel products.To produce low GI products, whilst maintaining the sensory quality of the product it is necessary to:

- reduce levels of simple sugars;
- decrease starch gelatinisation;
- build food structures in which metabolisable polysaccharides are protected and therefore release sugar more slowly during digestion; and
- replace starches with dietary fibre.

There are many available soluble and insoluble fibre sources that are already used in foods, but their increased use will require better understanding of their role in product structure in manufacturing processes, and also during breakdown in the mouth and human gut. Direct modification of plant sources to optimise fibre and reduce gelatinisation will initially require genetic intervention, until rapid breeding programs are established.

8.2.3 Protein and essential amino acids

Protein provides a source of nitrogen and essential amino acids for building and repairing muscle. The requirements identified by WHO provide a good basis for evaluating adequacy of protein supply.[113] These requirements vary with age from about 1.73 g/kg for a baby to 0.75 g/kg for an adult. A protein content of 25 g per 1,000 calories will meet the needs of all ages, and it is easy to see whether a given food is an adequate source of protein, when expressed in relation to calories.

The quality of protein depends on the level at which it provides the amounts of essential amino acids needed for overall body health, maintenance and growth. Animal protein, from eggs, cheese, milk, meat and fish, is considered high-quality (complete) because it provides a sufficient amount of the essential amino acids. However, these food sources are relatively inefficiently produced by current farming practice, requiring high inputs of both land and feed. Plant protein, from grain, corn, nuts, vegetables and fruits, is regarded as lower-quality because of lower levels of one or more amino acids. Fortification with added natural or synthetic amino acids has been practiced for many years, and will remain a vital contribution of the chemical sciences. However, masking of unacceptable flavour and taste from these additives remains a significant problem.

8.2.4 Micronutrients: the hidden hunger

Malnutrition is not just about insufficient calories. In many parts of the world, inadequate dietary iron, zinc, iodine and vitamin A cause significant ill-health which impacts on generation after generation. Both fortification and development of improved food sources can remedy this situation. Even in the presence of adequate nutrition, there is an increasing population of the elderly who cannot consume solid foods, causing effective malnutrition. Foods are needed which are palatable as well as nutritious.

In addition to trace minerals and vitamins, the role of antioxidants is increasingly identified with health protection, though their detailed mode of action is still under investigation. Even a diet that contains more energy than required for physiological needs can be deficient in micronutrients.

An individual's requirement of a nutrient is usually considered to be the amount that prevents symptoms of deficiency; however in recent years this has changed to the focus on the amount that minimises chronic risk of disease and optimises health. Nutrient requirements depend on factors such as age, gender and other genetic factors, level of physical activity, and state of health. The availability of rapid methods in genomics, proteomics and metabolomics is allowing study of the impact of diet on gene expression in individuals, and the individual's genetic sensitivity to food intake.

The restoration and fortification of food with micronutrients is required, but the bioavailability of the micronutrient must be verified. Novel ways of stabilising these compounds to provide release throughout the digestive tract are required.

Several technologies, many involving chemical sciences, can play a role in increasing the content and bioavailability of micronutrients of food, which are taken either as supplements, added to fortify existing foods or optimised in new raw materials and processes. Opportunities exist in the areas of:

- process and storage stabilisation;
- biomimetics;
- nanotechnology;
- encapsulation for targeted/triggered delivery (natural or synthetic; including multilayered structures);
- sustained release (kinetic control); and
- foods for vulnerable groups (infants/ adolescents/ elderly).

Increasing amounts of micronutrients can also be achieved through genetic modification. Different approaches are being exploited to produce transgenic rice enhanced in nutrients, for example with iron and provitamin A.[114] Research is underway to fortify rice and other food crops with folate, vitamin C and vitamin E. Sometimes, the enzyme stimulated by the nutrient is enhanced directly: for example the glutathione network, which is normally enhanced by selenium.[115] This technique could be most useful in helping to increase iron and zinc bioavailability in a diet free of meat, especially if the nature of the properties within meat which enhance bioavailability of these minerals could be elucidated.

8.2.5 Personalised nutrition

Although it is known that nutrition plays an important role in health and disease, often the cellular and molecular actions of nutrients are not fully understood. Human nutrigenomics (the study of how food and ingested nutrients influences gene expression) and nutrigenetics (how a person's genetic make-up affects a response to diet) provide routes to improve personalised nutrition. However, in order for either to develop further, rapid analytical techniques will be required to measure biomarkers of existing or pre-disease states.

The potential scope of research within the context of nutrigenomics and nutrigenetics is great and could include:

- genetic determinants of nutrient status, metabolic response and predisposition to diet related diseases (cardiovascular disease, diabetes, cancer, etc.); and
- nutrient regulation of gene expression, genetic determinant of responsiveness to nutritional therapy and/or diet-related disease progression, and the effects of dietary fatty acids on the expression of the genes involved in metabolic health, diabetes, cardiovascular disease, inflammation and colon cancer.

8.3 Consumer attitudes

A dialogue based on knowledge and an understanding of the social and cultural issues, together with a clear explanation to the public of the benefits as well as the risks of new technologies, is necessary between the public, government, regulators, media, NGOs and industrial representatives.

This section examines sustainability as it relates to consumer attitudes, primarily in developed countries where food is in ready supply.

8.3.1 Perception of risk

Consumers demand the right not to be unreasonably affected by the activities of science and technology. Total elimination of risk is usually not possible without giving up the benefits of the risky activity. Thus the concept of tolerable levels of risk is used to strike the balance between risk and benefit. However, we must recognise that perceptions of risk differ widely within society and around the world. To progress, science and technology must create a common understanding of benefits and burdens through providing information and through leading the debate in order to build trust amongst all stakeholders.[116]

People are often suspicious of new technologies because they are concerned that corporate profits may come before public safety. A dialogue based on knowledge and an understanding of the social and cultural issues, together with a clear explanation to the public of the benefits, as well as the risks, of new technologies, has the best chance of moving new technologies forward in Europe. It may well be that the training that chemists and engineers undertake – to examine data, generate hypotheses of cause and effect, and the building of complex models of system behaviour – now needs to be shared with the public at large, and this training should become introduced systematically and early in the education system. Public engagement to raise the profile of the chemical sciences at every stage of the food supply chain is critical.

8.3.2 Communication

Thus, with the introduction of any new technologies, there must be effective communication of the benefits as well as risks to the consumer and/or the environment, an alternative approach to that adopted with GM in the 1990s. Consumers want high quality, nutritious food at an affordable price in convenient packaging that does not have adverse effects on the environment. They are often bombarded with large amounts of often conflicting information about climate change, the environment, and new technologies in food production and waste disposal; and it is very difficult for them to make balanced judgements.

There is an urgent need to explain the principles of product lifecycles to the public at large. The complexity of sustainability is such that it would be impossible to summarise all the relevant information on a food packet. However, an initiative based on informing the public about the choices facing the UK food supply industry could help to raise awareness. Consumers are concerned about sustainability, and a public debate on technologies that can support sustainable food production needs to build on this. Society must understand that it is no longer possible to enjoy a wide variety of food at affordable prices unless science and technology are used to improve productivity. It may take a food shortage to bring this message home.

8.3.3 Behaviour

The consumer can have a profound influence on technologies that are adopted for animal and plant breeding, cultivation of crops and processing and packaging of food. Consumer purchasing power can determine the success or failure of a product in the market place. Public opinion is influenced by the media, education, and advertising and this can produce a preference for one technology over another. Environmental pressure groups, such as Greenpeace, Friends of the Earth or Forum for the Future, also play a role in informing and influencing public opinion.

A survey in 2006 identified that by far the most important thing for British consumers is the quality of food, with nearly 75% saying it is very important. For just over half of consumers, price is very important. For a third of consumers, a cluster of health, social and environmental issues were very important. These include: appropriate consumption of fats, sugars, and salts; health and environmental impacts of pesticides and other chemicals; fair treatment of workers; and, animal welfare. Interestingly, big environmental issues such as climate change and biodiversity in relation to food production and consumption were only seen as very important by about a quarter of respondents.[117]

A survey by the Food Standards Agency in 2008 found increased confidence among the public in the food they are consuming, and with regard to wider food issues.[118] Since 2006 there has been a decrease in the number of people concerned about issues such as food poisoning (36% down from 42%), additives (35% down from 38%) and GM foods (20% down from 25%). The survey also reveals encouraging trends regarding diet and nutrition, for example more than three quarters (78%) of consumers are now aware that we should be eating at least five portions of a variety of fruit and vegetables each day and 58% claimed to be putting this into practice by eating at least '5-a-day'.

Food labels remain important to shoppers looking for a range of information such as 'best before' dates, allergy advice, and additives in foods. Half of respondents said they check some form of labeling information when buying food. However, almost half of respondents in the survey did not know the difference between 'use by' and 'sell by' dates on food. The survey revealed that the amount of fat, saturated fat, salt and sugar in foods are still the top issues of concern among consumers and the quantity of fat and salt are the most commonly checked for nutritional information on labels.

In the 2006 survey consumers were asked how familiar they are with a range of information on product packaging. Four in five consumers have at least some familiarity with many forms of health, social and environmental product information. However, there are some exceptions, such as 'responsible fishing' labels, where less than half of consumers have any familiarity.[117] More than three in five consumers use, at least occasionally, a wide variety of product labels relating to health, social and environmental issues. In relation to health it is not just detailed nutritional information that consumers are using. More than a third of shoppers are frequently using healthy eating branding, such as "low fat range".

Increasingly, consumers have more sophisticated, exotic and diverse food interests; and demand for healthy, convenient food is rising. Food is seen by a segment of the population as a leisure interest and people spend increasing amounts of their time eating out.[119] Food safety and quality are the main priorities for most consumers, and increasingly a large number of consumers are using nutritional information on food labels to check the fat and salt content when purchasing products. However at the same time a study by the FSA in 2007, found that two-fifths of UK respondents find the print on labels hard to read, with nearly one third finding them difficult to understand. Given the concern over healthy eating, it is also important to note that almost half (45%) find it difficult to know, from the label, whether a product is healthy.[120]

Some studies have indicated that there is a significant gap between what consumers say they will purchase in hypothetical situations and what they actually buy.[121] In a recent Financial Times survey, 30% of people questioned claimed to take fair trade, animal welfare and environmental issues into account when making purchases, however the market share indicates that only 3% act on these concerns.

Consumers are driving change in food packaging by demanding less waste in their bins, according to the Waste Resources Action Programme (WRAP).[71] This will be reinforced if charging for the quantity of refuse collected is introduced. An Incpen consumer study on packaging found that 66% of consumers think that products are over packed.[122] However, the people most critical of packaging will buy packaged goods for convenience, even when an unpacked variety is available. Again, consumer opinion and personal behaviour are inconsistent. The retailers are in the strongest position to influence the minimisation of packaging materials and the setting up of recycling routes.

8.3.4 Controversial technologies

One key area in which public opinion in Europe has hindered the adoption of new technology is in the use of genetic modification techniques to breed higher-yielding strains of crops. The attempt to introduce products derived from GM crops into Europe more than ten years ago caused a backlash from consumer groups that fuelled public fear and suspicion of GM products. This led to a moratorium on the import of GM products and the growth of GM crops in Europe, which has only been lifted for a very limited number of non-food crops. As a consequence, the agrochemical companies developing products in this area reduced their presence in Europe and concentrated research and development in other regions of the world, such as the USA, China, India, Africa and Brazil. One third of the world's GM crops is grown in developing countries.

Opinion on the potential benefits of GM crops is strongly divided. Although trials of GM crops are underway in many EU countries, and one approved strain of pesticide-resistant GM maize for animal feed is being cultivated in several countries (notably Spain, France and the Czech Republic), many consumers claim that they will never buy or consume GM products. Greenpeace and Friends of the Earth argue that cultivation of GM crops decreases biodiversity and increases pesticide application rates. They claim that GM crops have done nothing to alleviate poverty and hunger in the world and that GM crops do not benefit the consumer.[123] They believe that we can use other food production technologies to meet the needs of the growing world population. The challenge is to produce realistic and robust data on which predictive models can be built, since the impact on agrochemical usage in maintaining, or even increasing crop yields will be compromised.

To be successful in securing consumer confidence, a different approach to the introduction of new technologies to that taken with GM in the 1990s is required, most likely based on effectively communicating benefits to the consumer. One of the problems for companies promoting GM crops is that the consumer does not see the benefits, in contrast to the use of GM in the pharmaceutical industry, where benefits to the public are much more obvious. Those in favour of GM crops argue that comprehensive safety testing has been carried out, to a much greater extent than for conventional crops produced by plant breeding. GM maize has been cultivated in the USA for more than 15 years with no apparent ill effects on consumers. A British Grassland Society survey found that 75% of UK farmers would be willing to cultivate GM crops if consumers would buy them; only 12.5 % of farmers said they would never grow GM crops.[124] With the world population set to increase by 50% by 2050, some believe that it will be essential to use GM crops to increase yield sufficiently to feed the growing population, without converting vast tracts of forest to agriculture.

At present British food prices are rising at their fastest rate since records began as a result of the continuing increases in raw material costs. Global prices are expected to continue rising by up to 20% over the next ten years according to the FAO. This may open up the debate on the potential for genetic modification of crops to help overcome food shortages in Europe. In the USA, higher-yielding GM corn varieties have helped farmers meet the 15% additional requirement for fuel ethanol.

European Member States are struggling to agree a policy on GM crops, with individual countries imposing their own bans on specific GM products. The UK Advisory Committee on Releases to the Environment (ACRE) points out that novel crops produced by non-GM breeding methods do not require extensive risk assessments, and that the current approval system is focused on the risks of new GM plants and ignores their benefits. It concludes that a more balanced regulatory approach is required, dealing with all novel crops and agricultural practices and allowing the assessment of both risks and benefits.[125]

Another controversial technology that is likely to become more prominent is the use of irradiation to sterilise food. This technique has considerable potential to prolong the shelf-life of food and reduce waste, but it requires consumer acceptance. Currently, food packaging and some herbs and spices are irradiated, but approval has not been granted for irradiation of most food, due to concern about consumer resistance. This is another example of a technology that requires the benefits to be assessed alongside the risks.

8.4 Chemical science applications

Technologies applicable to the health and wellbeing of the consumer can be found in the following table. This table also identifies the underlying science and technology disciplines necessary to develop these research areas. A multidisciplinary and interdisciplinary approach is essential, with input identified from organic, inorganic, physical and analytical chemistry, structural biology, biochemistry, medicinal chemistry and food science, materials and polymer chemistry and chemical engineering.

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Harnessing of analytical chemistry to design rapid, real-time screening methods, microanalytical techniques and other advanced detection systems to screen for chemicals, toxins, veterinary medicines, growth hormones and microbial contamination of food products and their raw materials. To detect that they are not contaminated at source or during distribution, storage and processing, and that they contain required nutrients and are safe and fit for purpose, thereby avoiding their (re)processing, transportation or recall, and avoiding waste.	✓	✓	✓	✓		✓	

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Technology to produce sugar replacers and natural low calorie sweeteners to improve nutrition and combat obesity.	✓				✓		
Formulation for sensory benefit.			✓	✓	✓	✓	
Targeting food composition for immune health.					✓		
Domestic hygiene – visible signalling.				✓			
Chemical labelling to enable traceability – rapid fingerprint methods.				✓			
Understanding the effects of prolonged exposure to food ingredients.				✓	✓		
Design of rapid screening real-time analytical methods, microanalytical techniques and other advanced detection systems to screen for chemicals in crops and food products, to improve safety and reduce waste through transporting contaminated food, e.g. antibiotics and growth hormones in meat and toxins in food.				✓			
DNA analysis for animal genotyping to establish breed quality and authenticity.				✓	✓		
Development of rapid sensors, such as ELISA, for detection of allergens in food materials and on food contact surfaces.				✓			
Efficacy testing and food safety of new food additives, such as natural preservatives and antioxidants.				✓			
Better understanding of the nutritional content of all foods so that we can produce food more efficiently for the life-stage nutritional requirements of humans, livestock and fish.				✓	✓		
Use of analytical methods to support life cycle analyses of the environmental impact of individual food products, packaging and materials.				✓			
The development of chemical treatments to remove pathogens from raw ready-to-eat crops without affecting eating quality or nutritional content.	✓			✓			
Development of new non-animal meat substitutes and analogues with improved texture and flavour.					✓		
Development of bacteriophages and bacteriocins with antibacterial activity against food-borne pathogens and spoilage by microorganisms.				✓	✓		
Application of food metabolomics to the quality and safety of food – molecular profiling of food products to generate more comprehensive molecular descriptions of biological systems, using analytical biochemistry techniques.					✓		

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Nutrigenomics and nutrigenetics to satisfy individual genotype, optimise nutrition & health, protect against disease and identify allergenic responses.					✓		
Better understanding of the relationship between human phenotype and the response of the body to nutrients.					✓		
Development of diet for vulnerable groups, such as neonates, adolescents and the elderly.					✓		
Understanding the role of gut microflora in sustaining health and the role of probiotics and prebiotics in promoting health.					✓		
Better understanding of the links between diet and cancer. For example, research into naturally occurring carcinogens in food such as acrylamide and mutagenic compounds formed in cooking.					✓		
Measurement of the synergistic burden on humans of toxic chemicals from different environmental and food sources.				✓	✓		
Understanding how a 'cocktail' of phytonutrients and other chemicals in food affect the uptake of specific nutrients to benefit health.					✓		
Use of the glycaemic load of food in understanding nutrition and the role of glucose in health and the onset of type II diabetes.					✓		
Modelling of the whole digestive tract for researching digestion of new food and ingredients.					✓		
Further development and understanding of fortified and functional food with specific health benefits, and the impact of minor nutrients on health.					✓		
Understanding the chemical transformations taking place during processing, cooking and fermentation processes, that will help to maintain and improve palatability and acceptance of food products by the consumer.	✓			✓	✓		
Multilayered systems, encapsulation and release for the slow delivery of macro and micro nutrients.			✓				
Release mechanisms to deliver bio-actives to specific parts and surfaces of the body.			✓				
Development of micro-sensors in food packaging to measure food quality, safety, ripeness and authenticity and to indicate when the 'best before' or 'use-by' date has been reached.				✓	✓	✓	

9 Supply chain waste

Waste arises at all stages of the supply chain (from agriculture, food processing plants, retailers, caterers, wastewater treatment plants, domestic refuse and garden waste), with typically 30% of raw materials ending up as waste, although this can be as high as 75% in some cases. These materials are costly to dispose of, and increasingly they are being seen as a valuable resource for recycling carbon and producing energy. Up until now, many of these waste materials have been discarded in landfill sites, where little or none of their value is recovered; and uncontrolled methane emissions contribute to global warming. Carbon dioxide emissions per processed tonne from landfill are high, even with state-of-the-art methane recovery systems. Increasing landfill tax and lack of landfill availability, together with a greater focus on corporate social responsibility and with tightening legislation, are encouraging alternative uses of food waste.

The EU Landfill Directive (9/31/EC) represented a step change, obliging the UK to reduce, by two thirds of its 1995 level, land-filling of biodegradable, municipal waste (largely household waste) by 2020. The targets are based on weight, and focus on biodegradable waste, owing to its potential for production of methane.

Under the Waste Implementation Programme, the Government is investing £90m each year in a recycling fund to incentivise local authorities. The landfill tax escalator has increased in recent years from £3 per tonne to £8 per tonne, bringing the cost of landfill disposal to £40 per tonne in 2009.[126] At this level it has become economic to find alternative, novel disposal routes. Some 350 landfill sites are due to be replaced by 2000 alternative private sector processing factories, which will produce energy and, in some cases, compost.

9.1 Reducing waste

Waste arises at all stages of the food supply chain and technologies should be adopted to improve the efficiency of waste disposal through reduction and recycling.

According to Defra's Food Industry Sustainability Strategy (FISS),[127] the UK food industry accounts for about 10 Mt per annum (10%) of industrial and commercial UK waste.

There are relatively few published formal studies of amounts of waste arising at each stage of the supply chain, but those that are available are relatively recent, e.g. WRAP 2007 (households),[21] PICME 2005 (chilled food manufacture),[128] CFA 2004 (chilled food manufacture).[71] Waste arises at all stages of the supply-chain for a range of reasons including:

- crop failure, spoilage, disease, pest damage;
- fertiliser run off;
- raw materials not meeting users' specifications (microbiological, chemical, physical, organoleptic);
- spoilage of raw materials;
- expiry of shelf-life;
- disruption of the chill-chain;
- insufficient/excessive/inappropriate processing;
- hygiene failure (contamination or inefficacy of decontamination);
- trading practices; and
- consumer behaviour.

FISS challenged the food manufacturing industry to reduce its own waste by 15-20% by 2010.[127] The food industry, from retailer all the way up the supply-chain, faces two particular challenges (coupled with opportunities) for achieving more sustainable waste management:

- **Minimising food industry waste:** the food industry is a major user of packaging (it protects products from damage, deterioration and contamination and helps avoid waste). The industry carries substantial obligations, linked to EU rules, to undertake or to pay for recovery and recycling of packaging waste (EU Packaging Directive 94/62/EC). Much of the industry's waste is biodegradable (waste food and associated by-products).

It is imperative to find an alternative disposal route to landfill (where methane is generated), such as recycling, pyrolysis or digestion and composting, where value can be derived.

- **Minimising household and catering waste:** much of this starts as food-industry products and packaging purchased from the manufacturers and major supermarkets. The food industry can therefore influence household behaviour for the better, through product and packaging design.

It is essential that there is sufficient infrastructure to recover and reprocess waste material collected from domestic and business premises.

9.1.1 Food industry waste

While targets have been set, there are uneven baseline data on the food industry's waste – particularly for food rather than packaging materials. There are detailed data for packaging waste in the case of larger companies obligated under the packaging waste regulations. However, there is a lack of robust data on the production and management of waste at a sub-sectoral level, or information on other waste. Levels of waste reuse, recovery and recycling vary considerably across sub-sectors.

Packaging and food waste are the two most significant waste issues for the industry. In terms of sales, supplies of packaging to the food and drink industry were estimated to be worth £5,800m in 1997, representing around 53% of the total value of the packaging industry at that time.[129] Although this does not directly correlate with tonnage, it does indicate the significance of the food industry in the packaging lifecycle.

An Environment Agency (EA) survey estimated total industrial and commercial waste arising in England and Wales in 1998/99 to be 75 Mt, of which the food and drink (and tobacco) manufacturing sector was responsible for 7 Mt. The survey also found that overall 'food waste' across all sectors was 2.6 Mt (some unquantifiable food waste is mixed in with packaging and other waste and is recorded in the general industrial and commercial waste stream). Of this, 69% was recovered, re-used or recycled, 25% was disposed of to landfill, and the balance mainly sent for treatment.[127]

According to FISS, the UK food industry is a major user of energy, accounting for around 126 TWh per year (equivalent to about 14% of energy consumption by UK businesses), and a major contributor to UK carbon emissions with 7 Mt of carbon per year. From an economic perspective, a 2003 study from the Environment Agency,[130] using modelling by Cambridge Econometrics and based on data from case studies, estimated the total cost to manufacturing of wasted natural resources to be £2,000m to £3,000m, equivalent to about 7% of total manufacturing profit.

The challenge for the food industry is to reduce the amount of food and packaging waste that is produced each year (both by the industry itself and by consumers of their products), without compromising food safety, and to recycle or otherwise gain value from the waste that does arise, within the context of a whole lifecycle analysis.

Processing and manufacture

In a Defra-funded study of a small number of chilled prepared food manufacturing sites,[128] it was found that the principal sources of waste arising on site were:

- poor quality production, e.g. over/under baking; the challenge being to understand the precise process to obtain desired organoleptic characteristics and food safety assurance;
- trimmings, e.g. scrapped pastry trim, bread crusts, tomato ends, vegetable peel – the challenge being to extract valuable materials or energy from this waste;
- problems with performance of machinery, e.g. mechanical mishandling particularly in the packing lines;
- packaging, e.g. raw material packaging, scrapped product packaging;
- disposal of good product, e.g. out of life; and
- market-'imposed', e.g. last minute customer order cancellations (sudden loss of demand may be related to weather or promotional campaign).

Business is under increased pressure to recover and recycle packaging. The EU Packaging Waste Directive requires 60% of packaging to be recovered by the end of 2008. In February 2008, the UK Government set higher targets for paper of 67.5% by the end of 2008, rising to 69.5% by the end of 2010. However, the paper industry has already exceeded these targets. There may be a proposal for a second phase of the review of the EU Packaging Directive 94/62/EC, which may consider prevention of packaging waste, re-use of packaging and the introduction of a specific reference to producer responsibility.

In the UK, approximately 2.5 Mt of container glass are used each year. In 2005, 1.26 Mt of glass packaging were recycled, 80% of which was used to make new packaging. Approximately twice as much green glass is imported into the UK than is currently produced, resulting in a significant surplus of recycled green glass. Additionally, clear (flint) and amber glass is not being recycled sufficiently to meet demand. When using recycled glass to make new containers, 315 kg of carbon dioxide is saved for every tonne of recycled glass used.[131]

Approximately 2 Mt of plastic primary packaging is used in the UK each year. 132,000 tonnes of plastic bottles were recycled in 2006 which equates to around 25% of the bottles sold – this compares to 3% in 2001. Plastic is often used in products with a short lifespan: most plastic packaging has fulfilled its first use within six months, yet it does not biodegrade and has the potential to last for many hundreds of years. For every tonne of recycled plastic used to make new containers, over 1.5 tonnes of carbon dioxide is saved.

In the UK, 13,000m steel cans and around 5,000m aluminium drink cans are sold every year: 70% of all steel packaging is recycled and just over 30% of aluminium packaging. All steel cans contain up to 25% recycled steel, and two thirds of all cans on supermarket shelves are made of steel. Recycling one tonne of steel cans saves 1.5 tonnes of iron ore, 0.5 tonnes of coal and 40% of water usage. The aluminium recycling process uses only 5% of the energy needed for the smelting process.

Approximately 60% of the 2.3m tonnes of corrugated case material produced in the UK is for food and drink distribution, so sustainability of the food supply is of paramount importance. Corrugated cardboard has a recycling rate of 84%: this is the highest recycling rate of any type of packaging in the UK. Approximately 30% of the paper used in the cardboard is virgin fibre from managed forests and 70% is recycled fibre, largely from used corrugated boxes. Supermarkets collect cardboard waste, which can be recycled up to seven or eight times, and sell it back to packagers.

Retail and distribution

Packaging is essential for keeping food safe and fresh; however its disposal contributes to waste, thus its minimisation and recycling contribute significantly to sustainability. Consequently, retailers are keen to be involved in optimising packaging. This is driving the use of chemical sciences in the quest for new materials, systems and technologies.

Reducing the level and weight of packaging for supermarket own-label products is now a key objective for retailers, with quick and easy wins realisable within the produce sector, e.g. significantly reduced weight of packaging for fruit and vegetables. As well as the need to focus on the packaging of own brand products at the point of supply, there has been significant activity around packaging used for the transfer of loose produce between supplier, depot and store. This includes the development of reusable plastic crates, and reusable and recyclable trays.

The replacement of plastic packaging, derived from oil, with alternatives like waste cellulose and corn- or potato-based plastics, and the creation of intelligent packaging systems, are technologies to be advanced. The development of biopolymers and bioplastics from plant polymers, sugars and vegetable oils will be required by the retail sector, and the chemical sciences have an obvious contribution to make here. Collaborative awards to develop new materials and processes have been sponsored by several public sector sources (e.g. DEFRA LINK, and Research Council grants).

Retailers have started to establish direct links with external expert bodies and institutions, and have provided them with funding to develop innovative packaging solutions. For example, Tesco in association with The Sustainable Consumption Institute at Manchester University have invested in a project to turn chicken feathers into packaging.[132]

9.1.2 Household waste

Household waste has also been a target for improvement via the Waste and Resources Action Programme (WRAP), which works alongside DEFRA's Waste Implementation Programme. WRAP aims to help deal with, in particular, municipal waste (largely household waste), which is where most food industry waste currently ends up. WRAP estimates that 35-40% of UK biodegradable household waste originates from purchases made from the four major food retailers.

It is important to discriminate between avoidable and unavoidable waste. WRAP estimated,[133] on the basis of a study of 2,000 households, that 6.7 Mt of food waste – approximately one quarter of food bought by consumers – is thrown away each year in the UK. However, only half of this waste was estimated by WRAP to be edible. About 1 Mt of this is dependent on refrigeration (i.e. chilling or freezing). Most of this discarded food ends up in landfill, producing methane. However, the embedded energy used to produce, package, transport and deliver the food to consumers' homes produces the equivalent of at least 15 Mt of carbon dioxide every year.[133]

Many consumers increasingly favour ready-prepared retailed food and eating out, over cooking from scratch. There are very few studies of the relative efficiencies and environmental impact of industrial production for retail food service systems and domestic preparation of equivalent food.

9.2 Dealing with waste

Further research and development to examine whole waste utilisation is required. This includes the screening of food waste to find and extract valuable biochemicals and investment in anaerobic digestion for improved process control, enhanced performance and increased energy yield. The surface chemistry of membranes should be optimised, minimising fouling and reducing cleaning costs, to improve the economics of recycling aqueous effluent from the food industry. Support and development of thermal processes, to improve the recovery of energy from dry food waste, should also be a priority.

There are many of potential uses for food waste, including production of high value biochemicals, compost, and energy. Composting is widely practised in the UK and it competes directly with anaerobic digestion for food waste. It is useful as a soil fertiliser or conditioner, but the process releases significant amounts of carbon dioxide and does not generate energy. The extraction of phytochemicals and prebiotics from plant residues is an emerging field, although disposal of the remaining fractions presents a potential problem. Whole waste utilisation is the key; application of the biorefinery concept to waste recovery and processing is required.[134, 135]

9.2.1 Biochemicals

Further research and development to examine whole waste utilisation will include the screening of food waste to find and extract valuable biochemicals.

Carbon recycling in closed-loop systems will become more important as a result of lifecycle analysis and reduction of waste. Maximising the value of raw materials through the production chain, value recovery, is an important part of this. It involves the efficient recovery of waste materials and refinement to products of maximum value and high market potential. In the food supply chain, human and animal waste represent a large reserve of carbonaceous materials. These materials hold considerable value; they can be processed to produce high value biochemicals, compost, or energy. The use of crops to produce biofuel or biochemicals requires the input of costly resources such as energy and water for cultivation and harvesting, in addition to this there are further processing costs. In contrast, the only cost in producing high value products from waste is that of processing, this is offset by the costs incurred by current disposal practices.

The Institute of Food Research (IFR) Sustainability of Food Chain Exploitation Platform aims to initiate research and development relevant to the exploitation of supply chain residues and co-products. A specific research objective is to create a better understanding of how to disassemble food materials, with the aim of exploiting this commercially in food and feed use. Factors driving the exploitation of supply chain residues are:

- legislation, e.g. the Landfill Directive, which has resulted from environmental and consumer pressure;
- a fall in size of the UK herd, reducing the quantity of co-product that can be diverted to animal feed;

- centralisation of food processing, allowing the economy of collecting waste at a single point; and
- energy cost and climate change (carbon emissions impact on all aspect of food production).

A wide variety of plant and food processing residues is available as feedstock for other products or processes. Typically ~30% of raw materials end up as waste. Examples of plant residues include cereals (excess bran from milling, brewers' grain, fruits), citrus (even after extraction of pectin polymers), pomace, olives and vegetable skins. Food processing residues include sugar beet pulp (~5 Mt annually in certain EU countries), brewers spent grain (3.4 Mt) and fruit pulp (>1.5 Mt). 'Mining' of this waste for starch, protein, lipids and phytochemicals with health-promoting properties is a new field of research.

There are difficulties in exploiting these waste residues, and these need to be addressed. Waste residues are unstable and subject to microbiological decomposition. They are derived from heterogeneous sources so that it is difficult to control quality.

Research is under way on methods to extract ferulic acid, an abundant phenolic phytochemical with antioxidant properties, from brewers' grain. An instant thickening agent has been extracted from onion waste. Prebiotics (which stimulate growth of beneficial bacteria in the colon) and antimicrobial agents are present in bergamot peel. There are many other opportunities awaiting investigation.

9.2.2 Compost

The composting process releases significant amounts of CO_2 and does not generate energy. Therefore, there is a need for investment in anaerobic digestion for improved process control, enhanced performance and increased energy yield.

In the UK, household waste (including household bin waste and waste from civic amenity sites) increased by 14% per person between 1995/96 and 2005/06, with each person generating just over half a tonne on average per year.

The amount of household waste recycled or composted in the UK has continually increased from 6% in 1995/96 to 26% in 2005/06. The amount of non-recycled waste per person has decreased in the last three years and is now at the lowest level since estimates were first made in 1983/84, most of this going to landfill.[136]

Composting produces a stabilised soil amendment, or compost product, which can be used as a fertiliser or soil conditioner to add organic matter back to soil, and to improve soil structure and moisture retention. Aerobic composting breaks down the organic material in the presence of oxygen with the microbes using nitrogen and carbon as the primary sources of food. Water vapour and carbon dioxide are the primary by-products.

There are two main methods of aerobic composting:

- turned/static aerobic windrow composting; and
- in-vessel aerobic composting.

In the UK, open turned aerobic windrows are the favoured option, even for non-green municipal solid waste and commercial waste. A number of in-vessel systems are operating on a small scale, and their ability to operate at higher temperatures allows increased treatment rate.

Large-scale composting projects are operated by the waste management companies, and many households practice small-scale composting. Some local authorities are encouraging this by providing householders with low-cost compost bins; others operate kerb side collection schemes for garden and food waste.

Other countries have much larger waste composting industries than the UK; the USA, France, Portugal and Spain all have relatively high rates of composting. Composting competes directly with anaerobic digestion (see below) for treatment of food waste. The UK composting industry at present lacks co-ordinated research. This has led to the 're-invention of the wheel' with regard to some research, especially that dealing with green waste composting, funded through the landfill tax credit scheme.

There is a need for longer term, strategic research covering process and quality control, including leachate and malodours as well as safety assurance (for example, zoonotic and plant pathogens).

9.2.3 Energy

Anaerobic digestion is rapidly becoming the best available technology to treat moist, organic food waste. Government subsidies for renewable energy are assisting this process. Anaerobic digestion generates renewable energy from biomass in the form of biogas, electricity or heat; and produces a fertiliser, which recycles nutrients to the soil. Although some carbon dioxide is released, the methane is converted to energy so that uncontrolled methane emissions are eliminated and much less carbon dioxide is released than for aerobic treatment or composting. Advanced thermal processes are beginning to establish themselves in order to produce energy from the drier, more solid food, and agricultural waste and packaging. Once investment has been made in these plants, food waste will become a valuable raw material. The precise mix of thermal processes, anaerobic digestion and composting will depend on local conditions and economics. Greater understanding of the biochemistry of these processes could lead to improved process control, enhanced performance and increased energy yield. Advanced computer process modelling can optimise effluent plant performance and efficiency as well as provide early warnings of process failure.

A raft of new chemical, thermal and biological processes is beginning to emerge to convert biomass waste into a variety of fuel including hydrogen, bio-crude oil and solid fuel. Energy recovery from waste will become increasingly important in providing on-site power generation for industry, combined with local heating schemes.

A number of technologies can be used to derive energy from food waste, as summarised in Table 2. Of these, anaerobic digestion has been used for many years to treat sludge from biological wastewater treatment and waste animal slurry. It converts organic waste with high moisture content, such as food waste, green waste and animal manures, in the absence of oxygen to biogas, which consists principally of methane (50-70%) and carbon dioxide. Combustion of the gas can generate electricity and/or heat, or it can be used directly to transport fuel. Optimum efficiency in energy conversion is achieved with combined heat and power (CHP).[137] It produces a solid digestate suitable for application to soil as a conditioner or fertiliser, and a liquor suitable for use as a liquid fertiliser. Until recently, anaerobic digestion has been used mainly as a waste treatment technology, with limited recovery of biogas for on-site power and local heating. The benefits of converting biogas to energy have now become more apparent as food companies struggle to reduce their carbon footprints.

Table 2: Technologies for energy from food waste

Technology	Intake materials	Energy/ fuel	Environmental considerations	Status
Anaerobic digestion	Biodegradable food & agricultural waste & packaging	Biogas for electricity and heat or motor fuel	Eliminates uncontrolled methane emissions, recycles nutrients to soil in sludge residue	Old established technology used for digesting sewage sludge & manure – current expansion to generate energy from food waste
Incineration e.g. poultry litter, straw, pelletised municipal waste	All food waste, electricity, steam & hot water	Disposes of contaminated materials	Long established technology for large volumes of low-grade waste or small volumes of hazardous waste	
Gasification	Wide range of biodegradable & non-biodegradable food waste	Gas for electricity & heat	IPPC designated as BAT	Long-established technology, currently re-emerging
Pyrolysis	Wide range of biodegradable & non-biodegradable food waste	Fuel oil for electricity & heat	IPPC designated as BAT	Long-established technology, currently re-emerging
Esterification	Waste cooking oil	Biodiesel transport fuel	Carbon footprint more favourable than growing crops for biodiesel	Several UK production plants
Fermentation & distillation	Starch-rich food processing by-products, such as potato waste	Bioethanol or biobutanol transport fuel	Carbon footprint more favourable than growing crops for bioethanol or biobutanol	Well established in Brazil and USA – first UK plant opened recently
Fermentation/ membrane separation	Biodegradable food waste	Hydrogen for electricity or fuel cells	Eliminates uncontrolled methane emissions	Future technology
Plasma	All food and packaging waste	Syngas	Produces vitrified material for construction	Future technology

Currently, there are only a few anaerobic digestion plants in the UK treating food waste, but many more are on the drawing board. The Government has been working with WRAP (Waste Resources Action Programme) to reclassify the digestate as a 'non-waste' so that it can be used more widely as an agricultural fertiliser. At present, farmers must have a licence or an exemption in order to use the digestate. The Government is also doubling the subsidies available to producers of renewable energy under the Renewable Obligation Certificate scheme. WRAP is currently conducting a food waste collection trial for anaerobic digestion with 16 local authorities, and reports 60-80% participation rates. Leicester City Council has a municipal anaerobic digester which accepts mixed organic waste. Major retailers are trialling anaerobic digestion as a way of both reducing the amount of waste that they send to landfill and of producing heating for stores.

Anaerobic digestion has the advantages of being able to generate energy from waste on a local scale. The diversion of food waste from landfill to anaerobic digestion reduces uncontrolled emissions of methane, and helps to recycle nutrients back to the soil. The process is tolerant to rogue materials, such as glass or plastic, which can be removed in the reception tank.[138] Anaerobic digestion works well in the tropics, due to the higher temperatures, and recent UK studies have focused on operating the process at higher temperatures. A greater understanding of the biochemistry of anaerobic digestion could lead to improved process control, performance and energy yield.

Sweden is a leader in the recovery of energy from biomass: 25% of all energy used in Sweden is derived from it. Biogas-powered buses are widely used, and the first biogas-powered train runs between Linköping and Västervik. Biogas is produced at a sewage treatment plant in Västervik and at an abattoir in Linköping, and all urban transport in Linköping now uses biogas. Biogas fuel releases only one fifth of the nitrous oxide generated by diesel.

Waste that is not suitable for recycling or anaerobic digestion can be treated by a variety of thermal methods to produce a solid, liquid or gas fuel. Incineration with energy recovery, gasification and pyrolysis all thermally degrade waste, converting the majority of the carbon to carbon dioxide, and recovering energy as electricity and/or heat. Energy in the form of electricity can be transported to the national grid, and heat-energy can be used for local heating.

Gasification and pyrolysis of biomass waste are technologies that were developed during the Second World War and subsequently abandoned; they are currently re-emerging as effective methods of recovering energy from biomass. They can accept a wide range of feedstock, and they can be applied to many types of industrial waste. Pyrolysis heats organic waste without oxygen to produce oils and combustible gases at relatively low temperatures (400 °C to 800 °C) Gasification uses oxygen to produce a gas at temperatures ranging from 88 °C to 1,400 °C. A renewable energy plant is under construction at Immingham, Lincolnshire to convert 170,000 tonnes per annum of food and non-recyclable packaging waste into a stable biomass fuel.[139] The location was chosen due to its proximity to the UK's largest food manufacturing cluster. The biomass fuel is vaporised to a clean gas (similar to natural gas) using advanced gas conversion technology, before being fed into conventional gas engines to generate 24 MW of renewable energy for supply to the national grid. The residual ash (2-5% of the original volume) is used in the construction industry. The construction of a further ten plants over the next five years is planned.

A new thermal hydrolysis technology has recently been approved by the Canadian Food Inspection Agency for the safe destruction of hazardous materials, such as waste tissue from livestock. The high temperature, high pressure process, piloted over several years, enables the redirection of waste material, previously shipped to landfill, into biogas for the generation of electricity and thermal energy. The resultant solids are approved for use as a land amendment.[140]

Pyrolysis of timber and other organic matter at high pressure produces an oil to fuel a power plant. A number of patents have been filed covering the production of fuel briquettes from refuse and sewage sludge, but this fuel has encountered regulatory difficulties. An improved understanding of the reactions governing pyrolysis and gasification could lead to improved energy yield.

Waste cooking oil and tallow can be converted into biodiesel in a simple esterification process that can be carried out on a relatively small scale. 75,000 tonnes of waste vegetable oil and 100,000 tonnes of tallow are generated from catering and industrial sources annually in the UK. A number of companies collect this oil and convert it into biodiesel, which is then blended with diesel to produce a transport fuel. The quantities of waste cooking oil available are limited, so that rapeseed oil is used as an additional feedstock in biodiesel plants. Algae from aquaculture are also being evaluated as a raw material for biodiesel production.[141]

Due to the complexity of the fermentation and distillation process required to produce bioethanol, large plants with economies of scale, using crops as a feedstock, tend to be the most economic production route. However, there are some examples of the production of bioethanol from starch, sugar or ethanol waste at facilities where the waste arises. In the USA, for example, brewery waste, beverage waste and cheese whey are fermented to fuel ethanol.[142] The fermentation process also produces a protein-rich animal feed, which recycles part of the organic material into the supply chain. Biobutanol also can be produced by fermentation, and a process to ferment it from corn, sugar beet or grass is under development.[143] Biobutanol has a higher energy value than ethanol, and it is less water soluble and evaporative, making it safer to transport in existing fuel pipes.[144]

An alternative process route to bioethanol has been developed in the USA – using household waste, wood, plastic bottles and tyres to produce ethanol. The waste is converted to carbon monoxide and hydrogen, which are processed by bacteria into bioethanol.[145] In Australia, CSIRO has developed a process that turns green waste, including forest thinnings, waste paper, crop residues, and garden waste, into a stable bio-crude oil. The bio-crude oil can be produced locally and transported to refineries for further processing into biofuel.[146]

A highly innovative, new membrane separation technology converts organic waste into hydrogen in a two-stage fermentation process.[147] The hydrogen can be converted into electricity via thermal treatment, used in a fuel-cell or directly as fuel. A number of hydrogen-powered cars and buses are currently being trialled. Fuel-cells can covert fuel into power with 40-50% efficiency, as compared with 18% efficiency of the internal combustion engine. Hence, they could significantly reduce the amount of fuel needed for food production and supply in the future. Electrochemistry has a major role to play in the development of economically-viable fuel-cells for transport.

Another technology at the forefront of research and development in energy from waste is plasma treatment, which uses a plasma torch to heat waste. A clean syngas with a high calorific value is produced from organic waste, along with a non-leachable vitrified lava from the inorganic substances. Plasma is a very hot gas, characterised by the ionisation of its atoms. It has higher energetic densities and capacities of heating than conventional thermal heating methods. Plasma can treat all types of waste; although, due to its high cost, early applications are likely to be for hazardous waste. Plans are underway to install a plasma torch in South Korea to produce energy from sewage sludge.[148]

9.2.4 Aqueous effluent

The Water Framework Directive is tightening standards for discharge of effluent to watercourses, and this is encouraging the food industry to adopt new treatment technologies able to 'polish' effluent to high standards.

The recycling of aqueous effluent from the food industry requires research into the surface chemistry of membranes, optimised to minimise fouling and reduced cleaning costs, and to improve the economics of recycling effluent from the food industry.

Food-processing effluent is typically high in biochemical oxygen demand (BOD) and suspended solids, and a variety of different effluent treatment technologies, including chemical, physical, aerobic biological, reed bed, membrane and anaerobic digestion treatments are employed by the industry.[149] Chemical treatments are used to precipitate inorganic contaminants or to neutralise effluents; fat and oils are removed in oil/water separators, and suspended solids can be removed using dissolved air flotation. Reed beds (artificially engineered wetlands which optimise biological, physical and chemical treatment of contaminants) can be used for treating diffuse pollution in rural environments. Aerobic treatments, such as activated sludge, have been used widely in the UK for food-industry effluent and, more recently, membrane bioreactors have been introduced to recover product and to produce high quality final effluent suitable for recycling.[150] The ultrafiltration membranes used in membrane bioreactors are expensive, but water and effluent costs are eliminated if the resultant effluent can be recycled in a zero discharge process. Microfiltration, ultrafiltration, nanofiltration and reverse osmosis membranes are all used for water treatment, depending on the size of the molecules to be removed or recovered.[149] Improvement in the surface chemistry properties of membranes could increase process viability by reducing fouling and cleaning requirements. The energy cost of aeration in aerobic treatment processes is a major drawback. Anaerobic digestion (see above) has been used for many years for treating food industry effluent in the USA and other European countries, and its ability to produce biogas for energy is encouraging its use in the UK, as discussed above.

Novel chemical and biochemical treatments under development for removing contaminants from effluents or irrigation water include immobilised polyphenoloxidase enzymes to remove phenolic compounds[151] and silica particles coated with a nanometer-thin layer of adsorbent material to remove toxic chemicals, bacteria and viruses.[152]

9.3 Chemical science applications

Technologies applicable to supply chain waste can be found in the following table. This table also identifies the underlying science and technology disciplines necessary to develop these research areas. A multidisciplinary and interdisciplinary approach is essential, with input identified from organic, inorganic, physical and analytical chemistry, structural biology, biochemistry, medicinal chemistry and food science, materials and polymer chemistry and chemical engineering.

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of novel in-line chemical sensors for improved process control by optimising conditions and inputs during food processing, and chemical addition during effluent treatment.				✓			✓
Packaging for food that is compatible with anaerobic digestors.						✓	
Recycling mixed plastics to recover monomers.	✓	✓				✓	✓
Sensors to replace sell-by dates.	✓	✓	✓	✓	✓		
Analysis of the composition of composts, digestates and waste biomass to monitor quality, to verify and validate processes and to assist with certification.				✓			
Use of analytical methods to support life cycle analyses of the environmental impact of individual food products, packaging and materials.				✓			
Extraction and application of valuable ingredients from food waste, e.g. enzymes, hormones, phytochemicals, probiotics and chitin.	✓	✓			✓	✓	✓
Polymer chemistry to develop new biodegradable, recyclable or multifunctional packaging materials, to reduce environmental damage and the quantity of packaging used in the supply-chain.						✓	
Understanding the metabolomics of spoilage of crops and food, to reduce losses.							
Identification and application of novel enzyme chemistry for modifying ingredients, such as proteins.	✓				✓		
Understanding the fundamental chemistry and biochemistry of anaerobic digestion and the generation of biogas to improve yield and efficiency.					✓		✓
Understanding the biochemical processes involved in produce ripening, food ageing, enabling shelf-life prediction and extension and reduction of waste.				✓	✓		
Development of bioremediation technologies using microorganisms, and other living organisms, to degrade or detoxify environmental contaminants in soil, so reclaiming it for agricultural use.					✓		✓

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of new methods for the efficient use, purification and cost-effective recovery of water in food processing, leading to water-neutral factories.							✓
Development of more efficient processes allowing the reuse of treated effluents and greywater, and the desalination of seawater for irrigation.				✓			✓
Application of portable reactors for treating diffuse pollution.							✓
Production of biofuel, such as biodiesel and bioethanol, and renewable energy from agrifood waste.	✓				✓		✓
Development of efficient anaerobic treatment plants to process farm, abattoir and retail waste, so generating biogas for energy.							✓
Further development of the biorefinery concept, to make maximum use of raw materials and by- and co-products, by making a range of products at a single site and maximising energy efficiency.							✓
Development of closed-loop recycling of carbon and other nutrients, for example, using agricultural waste to provide energy and fuel for local farms and businesses.							✓
Use of mass, heat and energy transfer principles, combined with advanced data handling, to minimise losses of product, water and energy throughout the supply-chain.							✓
Development of improved routes for by- and co-product processing to reduce waste and recover value.							✓
Development of improved slaughtering techniques and processes using less energy to recover by-products and reduce waste. Reduction of carcass contamination from abattoirs by developing technologies such as handheld steam pasteurisation.							✓
Development of immobilised enzyme systems for food processing and to treat liquid waste, so increasing efficiency and reducing waste.			✓		✓		✓
Optimisation of conditions for thermal methods, such as gasification and plasma, for generating energy from agrifood waste.			✓				
Understanding the chemical transformations taking place during processing, cooking and fermentation processes, that will help to maintain and improve palatability and acceptance of food products by the consumer.	✓			✓	✓		
Development of processes and systems improving the recyclability of plastics, glass and cardboard, for example by enhancing the properties of recycled cellulose fibres.						✓	✓

Application	Underpinning science & technology						
	Organic chemistry	Inorganic chemistry	Physical chemistry	Analytical chemistry	Structural biology, biochemistry, medicinal chemistry and food science	Materials and polymer chemistry	Chemical engineering
Development of single-layer meat packaging to replace the multilayer packs containing gas-impermeable, water-resistant and rigid layers.						✓	
Development of biodegradable or recyclable, flexible films for food packaging, e.g. corn starch, polylactic acid or cellulose feedstock, able to withstand the chill-chain, consumer handling, storage and final use (e.g. microwave or conventional oven).						✓	
Use of waste products as feedstock for packaging material, for example the production of a novel biodegradable plastic material made from epoxides and CO_2.						✓	
Development of smart packaging capable of absorbing oxygen to preserve the freshness and shelf-life of food (with food safety caveats requiring assessment in relation to anaerobic pathogens).				✓		✓	
Development of chemical methods for removing paper labels and printing inks from recycled packaging.	✓	✓				✓	✓
Improved understanding of fibre technology to enable the development of materials for the hygienic storage and transportation of raw materials.						✓	
Development of improved, more cost effective fouling-resistant materials for use as membranes in food processing and effluent treatment.						✓	✓
Application of electrokinetics to extract and recover water from waste for recycling.			✓				
Development of functional (i.e. antimicrobial) and intelligent packaging films providing specific protection from moisture, and lipids improving texture and acting as carriers for various components (e.g. nanotechnologies).			✓			✓	
Application of surface-coated particles to remove biological contaminants from drinking water by electrostatic attraction.			✓	✓		✓	

10 Resourcing and support

Technical skills are essential to maintain safety in the food supply chain and to increase competitiveness. However recruitment into technical, engineering and operational roles is a problem. In the future, this will compromise the competitive ability of the UK food supply chain and its capacity to deliver on consumer expectations.

In 2008, labour market information identified that around 432,000 are employed in the food and drink manufacturing sector alone in Great Britain.[153] This sector turns over £74bn each year, £22bn of which goes to the Treasury. The industry is vital to the sustainability and competitiveness of the UK economy. A survey of 1200 food and drink manufacturers in the English regions found one in five employers with current vacancies and around one in 20 with hard to fill vacancies.[154]

Sectors of the food supply chain have a poor image for potential employees and as a result people considering their career options are put off applying for related vocational and academic courses and for jobs.

10.1 Education and training

Every student in every UK secondary school should have access to first rate teachers of the main STEM subjects – physics, chemistry, biology and mathematics – each trained and qualified in their subjects, kept up-to-date through continuing professional development (CPD), and supported by a full range of support facilities, services and materials, with the financial resources to use them.

It is necessary to improve the training of careers advisers and the information resources available for secondary school students, specifically regarding the possible career paths open in modern food production. Career opportunities in the food supply chain sector must be promoted through work experience placements, teaching placements, careers events and media engagement.

The UK Government has recognised the vital importance of increasing the numbers of young people studying science, technology, engineering and mathematics (STEM) subjects and raising the levels of STEM literacy among those entering adult life. The supply of STEM talent directly impacts upon the ability of the science and engineering-based industries to continue to play their crucial part in the UK economy. Entrants to university courses show significant signs of improvement in chemical science, with a 31% increase in entrants in the last 5 years, however in real numbers this only brings them back to the level they were at in 1997; and the longer term situation for science and engineering as a whole remains one of real concern.

From an international perspective, the importance of STEM to the UK is hard to overstate. For example, there is clear evidence that one of the most important factors in determining where large multi-national companies locate knowledge-based research and development (R&D) linked investment is access to a pool of skilled and talented people. The UK is losing its competitive advantage in this respect and, unless the trend is reversed, there is little hope of achieving the national inward investment objectives or the relevant targets enshrined in the "Lisbon Strategy". This point is also emphasised in the recent Leitch Review[155] which stresses that 'valued' skills are essential for the UK to maintain or improve its position as an economically successful nation. To achieve this, the nation as a whole will have to contribute more to the development of higher quality skills.

It is not only the economic and financial health of the nation that depends on STEM. This report shows that progress towards tackling key issues in the food supply chain are dependant on a number of underlying science and technology disciplines including chemistry, physics, biology and chemical engineering.

10.1.1 Skills gap

The Roberts Review sought to address the matter of the balance between supply and demand of high quality scientists and engineers as a key element of the UK's future research and development (R&D) and innovation performance.[156] The review acknowledged that the number of students studying for scientific and technical qualifications was relatively large in comparison with other countries and was growing. However it noted that the growth was chiefly due to increases in the biological sciences and IT which masked a downward trend in numbers studying mathematics, engineering and the physical sciences. Importantly the Roberts Review did acknowledge that chemistry, along with other sciences, technology, engineering and mathematics, is a 'strategically important and vulnerable subject'. Strategically important to the economy and to society both now and in the future, vulnerable in the case of chemistry, in that there is a misalignment between provision and regional subject priorities.

According to a Royal Society report, between 1992 and 2006 the number of A-level entries in the UK grew by 10%, from 731,000 to 806,000.[157] Within this context of increasing overall numbers there have been decreases of 6% in the number of entries to chemistry (from 43,000 to 40,000); 34% in physics (from 41,000 to 27,000); and 13% in mathematics and further mathematics (from 72,000 to 63,000) with the decrease occurring mainly in mathematics rather than further mathematics. The number of A-level entries to biology has fluctuated but increased by 13% overall during this period (from 49,000 to 55,000). Entries to science and mathematics Highers have fallen over the same period, although the fall in mathematics appears less marked than for A-levels.

More recent data from the RSC show that following the major curriculum change of 2000, the number of A-level entries in the UK grew by 4%, from 774,000 in 2000 to 806,000 in 2007.[158] During this period of time the number of entries to chemistry and biology have remained relatively stable (at approximately 40,000 for chemistry and 55,000 for biology); physics entries have decreased by 16% (from 32,000 to 27,000); mathematics and further mathematics entries have increased by 3% (from 66,000 to 68,000). The total number of entries to Highers between 2000 and 2007 has decreased by 1%. Entries to chemistry have decreased by 5% (from 10,000 to 9,500); physics by 15% (from 10,000 to 8,500); mathematics and further mathematics by 10% (from 21,000 to 19,000); and biology by 10% (from 10,000 to 9,000).

The Royal Society report identified that since entry to medicine, dentistry and veterinary sciences courses is highly competitive, often requiring three A grades at A-level, these subjects take a high proportion of the students achieving the top grade in A-level/Advanced Higher chemistry and biology. Medical school places have been expanding rapidly – up 70% between 1997 and 2004 – during a period when numbers of entrants to chemistry A-levels have decreased. The combination of these two trends puts real pressure on the pool of good students who could take first degrees in chemistry.

The Royal Society also re-analysed Higher Education Statistical Agency (HESA) data which showed that an increasing proportion of all first degrees are being awarded in the sciences broadly interpreted – up from 31% in 1994/95 to 37% in 2004/05. However, much of this increase is attributable to the categories of computer science (up from 3.7% of all degrees in 1994/95 to 6.3% in 2004/05, but now decreasing) and subjects allied to medicine (up from 4.9% to 9.8%).

The latest figures from UCAS are more positive. In 2008-09 universities' acceptances of students in chemistry have risen by 4.4%; physics by 3.3%; and mathematics by 8.1%. These increases build upon those seen between 2005-06 and 2007-08 when chemistry increased by 12.1%; physics by 10.3%; and mathematics by 12.4%. While universities' engineering acceptances fell by 0.8% between 2005-06 and 2007-08, they have increased this year by 6.4%.[159]

The Leitch Review looked into projections of the overall skills requirements of the economy to 2020. However it did not break up the broad occupation types into the further detail that would be necessary for looking at employment in STEM occupations. Instead projections of employment, drawn from Working Futures 2004-2014[160] in some STEM occupations in 2014 can be seen in Table 3.

Table 3: Projected employment in STEM occupations in 2014[160]

	Science and technology professionals (SOC code 21)	Health professionals (SOC code 22)	Science and technology associate professionals (SOC code 31)	Health associate professionals (SOC code 32)	All other occupations (All other SOC)
2004 (baseline)	947,000	277,000	593,000	1,045,000	26,449,000
2014 (forecast)	1,121,000	360,000	666,000	1,122,000	27,314,000
Change (%)	18%	30%	12%	7%	3%

Source: Sector Skills Development Agency Working Futures 2 (2006)

These projections suggest an increase in the demand between 2004 and 2014 for science and technology professionals and science and technology associate professionals of 18% and 12% respectively, compared to an increase for all other occupations of 4%.

Recruitment difficulties in STEM occupations can be seen as an indicator of the balance between demand and supply. The National Employer Skills Survey (NESS) 2005 data show that two of the STEM occupational groups, engineering professionals and health associate professionals, were above average in terms of the number of skill shortage vacancies (SSVs) and the density of skill shortage vacancies (skill shortage vacancies per 1,000 employees).[161]

Independent research by PriceWaterhouseCoopers commissioned by the RSC and the Institute of Physics (IoP) shows that the average chemistry graduate does very well in terms of their salary, earning substantially more over a lifetime than graduates of many other disciplines. In fact, over their lifetimes, graduate chemists earn (on average) up to £190,000 more than those with two or more A Levels (no degree), and £60,000 more than most other graduates, including those with degrees in subjects like history, English, psychology and biological sciences. This indicates a higher than average value for these skills.[162]

The projections of increases in supply of STEM skills and progression rates to STEM jobs would suggest that, at a broad level, supply is likely to meet the increase in demand for these skills over the next 10 years. However there may be problems with specific subjects. On current trends the increases in supply of engineering and physical sciences are relatively low, and with over half the graduates in these subjects not going on to STEM occupations straight away, there is a possibility that demand for these skills will not be met by supply.

Food and drink manufacturers

There is considerable concern about the skills gap that threatens the productivity of the UK food and drink manufacturing industries. Over a fifth (22%) of all employers contacted in a survey of 1,200 UK food and drink manufacturers believe that the skill needs within their establishment will change over the next 2-3 years. Half of employers who think their establishment's skill needs will change in this time frame identify technical, practical or job-specific skills as those that will need improving.[154]

In addition, a minimum of 56,000 workers are expected to retire from the sector over the next eight years while there are fewer 16-29 year olds available to replace this older cohort. Overall replacement demand for the sector is expected to be 118,000 by 2014.[163]

The sector has difficulties in recruiting sufficient graduates for its needs now, and this is likely to continue to be the case in the future. This is in part due to the image of the industry; the sector is not one that is particularly highly regarded as a career path. Thus it can be difficult to encourage skilled scientists and engineers to take up the required food science and engineering roles.[163]

Improving the supply of people entering the sector is the way forward.[164] Raising the profile and improving the image of roles in sectors of the food supply chain, such as the food and drink industries, placing more emphasis on training, encouraging people to study STEM subjects, and supporting science teaching of STEM subjects at school are viewed as ways to increase the supply of skilled scientists and technologists to meet the needs of the sector. Closer links between food sector industries and universities and their students should be facilitated to ensure graduates have the appropriate skills mix for sustainable food production.

10.2 Research and collaboration

Closer links between food sector industries and universities and their students should be facilitated to ensure graduates have the appropriate skills mix to deliver sustainable food production.

A clear communication programme is required between grant funders and potential grant holders in order to optimise funding mechanisms.

To enable research at interfaces, Higher Education Institutions (HEIs) need to assess whether they are providing an appropriate infrastructure to enable inter- and multidisciplinary research. HEIs should look at their structures to identify administrative barriers that impede collaboration, such as different departmental cost structures, and to seek harmonisation.

Food innovation and particularly food safety is crucially dependent on the role and work of scientists and technologists in the food industries, in academia and research, in government departments and agencies, in food law enforcement, in local authorities, and in consultancies.

For example, in 2001 the FSA published a detailed review of the research they fund and how they manage it. Data provided on the breakdown by contractor of committed spend on research projects shows a fair distribution between universities, government and private research institutes, see Table 4.[165]

Table 4: Breakdown by contractor, of FSA committed spend on research projects

Name of contractor	%
ADAS	6
Centre for Environment, Fisheries and Aquaculture Science	5
Central Science Laboratory	7
Institute of Food Research	7
Leatherhead Food Research Association	1
Laboratory of the government Chemist	2
National Radiological Protection Board	1
Public health Laboratory Service	4
Rowett Research institute	3
TNO-BIBRA	1
Universities	36
Veterinary Laboratories Agency	2
Others	25
Total	100

Meeting the chemical science and engineering opportunities outlined in this report depends both on applying current understanding and developing new knowledge. Both activities are the responsibility of science and technology.

An understanding of all aspects of the science that underpins the supply of safe and high quality food depends on the maintenance of coordinated research and expertise in this area. Importantly, research must be both inter- and multidisciplinary.

Interestingly, the European Commission FP7 has allocated €32,413 million to the cooperation programme.[166]

This is a specific programme that supports all types of research activity carried out by different research bodies in trans-national cooperation and aims to develop or consolidate leadership in key scientific and technology areas. This funding is available to support cooperation between universities, industry, research centres and public authorities throughout the EU and beyond. Among the ten themes within the cooperation programme is 'Food, Agriculture and Fisheries, and Biotechnology', which aims to promote European leading and innovative knowledge to increase productivity and competitiveness and to improve quality of life, while protecting the environment. The EU Member States have earmarked €1.9 billion for funding this theme over the duration of FP7.

10.2.1 Interdisciplinary research

Research in the biological sciences is increasingly dependent upon inputs from chemistry and the physical sciences. Accordingly, the RSC commissioned a report, 'Face to Face: UK Chemistry-Biology Interface' to provide information on the chemistry community's participation in bioscience research.[167] The report sets out key recommendations for academia, research institutions and funding bodies in the UK for facilitating interdisciplinary and multidisciplinary research in this area and also highlights issues that will be of interest for policy-makers up to the national level.

The chemistry-biology interface is a burgeoning area of interdisciplinary research that plays a vital role in advancing understanding of the fundamental principles underpinning biological systems and has high relevance to the treatment of human diseases and has very significant potential for wealth creation.

Although the RSC report focuses on research across the chemistry-biology interface, findings may also provide insights for research at the interface between other disciplines such as chemistry and engineering.

Interestingly, 42% of respondents surveyed for the RSC report identified that they did not feel that current undergraduates would be equipped to do research at the chemistry-biology interface. Institutions must ensure that training is available to PhD level across departments. Further study is necessary to assess existing mechanisms for providing adequately trained interdisciplinary researchers.

Mechanisms that were reported to be in place in institutions to support multidisciplinary and interdisciplinary research include: facilitating physical proximity and promoting interaction at a personal and departmental level (although infrastructure is seen as important, it is not pre-eminent in facilitating effective collaboration); interdisciplinary centres (including physical buildings and virtual centres); regular inter-departmental seminars; joint undergraduate course provision; cross-departmental PhDs; and joint faculty appointments.

Lessons drawn from studying the chemistry-biology interface are likely to apply to other interdisciplinary areas such as food research. There remains a perception within the chemistry-biology interface research community that the complex array of schemes offered by the funding agencies is not entirely user-friendly. It is thus imperative therefore that in facilitating interdisciplinary research, there is clear and concise support and resources from government departments and agencies, universities and sponsored institutes.

Critical to advances in food research will be effective interdisciplinary collaboration between academia, industry and government to coordinate long-term strategic research.

Appendix A

Working Party

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Appendix B

Questionnaire

This structured questionnaire was used to guide interviews with contributors. It was sent to them ahead of the interview, and completed by the interviewer after discussion.

<table>
<tr><th colspan="4">Acumentia Ltd Chemistry and Food Sustainability Questionnaire</th></tr>
<tr><td rowspan="3">Acum-
entia use</td><td rowspan="3"></td><td>Name</td><td></td></tr>
<tr><td>Company</td><td></td></tr>
<tr><td>Date</td><td></td></tr>
<tr><td rowspan="13">Pre-amble</td><td rowspan="10">We have been engaged by the Royal Society of Chemistry to produce a report on the role of the chemical sciences in the sustainability of food production. Our brief is to take a global perspective; however, its aims will be primarily to influence UK and European policy. The scope covers chemistry, chemical engineering and biochemistry, and we want to take a short-term (now), medium-term (5-10 year), and long-term (20 year) view.

The definition of sustainability we are using is taken from the World Commission on Environment and Development (the Brundtland Report):

'Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their needs.'

We are interested in technologies that apply to the sustainability of the total food supply chain over the next 20 years, with particular emphasis on the role of the chemical sciences in relation to the areas listed opposite, and described in the diagram below.

Please give an indication of the interviewee's areas of expertise, to which the answers below will relate.</td><td>Fresh water / soil / air / sea</td><td></td></tr>
<tr><td>Primary Production</td><td></td></tr>
<tr><td>Feedstuffs</td><td></td></tr>
<tr><td>Ingredients</td><td></td></tr>
<tr><td>Processing & preservation</td><td></td></tr>
<tr><td>Packaging</td><td></td></tr>
<tr><td>Distribution</td><td></td></tr>
<tr><td>Retail</td><td></td></tr>
<tr><td>Consumer</td><td></td></tr>
<tr><td>Waste</td><td></td></tr>
<tr><td rowspan="3"></td><td>Nutrition</td><td></td></tr>
<tr><td>Analysis & diagnostics</td><td></td></tr>
<tr><td>Environment & economics</td><td></td></tr>
<tr><td>Q1</td><td>What do you think are the key areas, challenges and opportunities for the sustainability of the food supply over the next 20 years?</td><td>Areas</td><td></td></tr>
</table>

		Challenges	
		Opportunities	
Q2	How important strategically is the sustainability of the food supply to your company/organisation?	Answer	
Q3	To what extent is your company/organisation involved in any way with the sustainability of the food supply?	Answer	
	For example, does it take steps to ensure the sustainability of raw materials or make interventions in the food supply such as:	Preservation of stock	
		Breeding programmes	
		Water, soil, air quality	
		Waste control	
		Distribution methods	
		Preservation methods	
		Packaging	
		Research programmes / funding of projects, etc.	
Q4	What relevant technologies are **currently** being used in [specific] [any] areas?	Current	
	What are the **emerging** technologies in [specific] [any] areas?	Emerging	
	What **future** technologies, yet to be created, would you like to see in [specific] [any] areas?	Future	
Q5	How do **current** technologies contribute to the sustainability of the food supply?	Current	
	How do **emerging** technologies contribute to the sustainability of the food supply?	Emerging	
	How would **future** technologies contribute to the sustainability of the food supply?	Future	
Q6	What are the strengths and weaknesses of **current** technologies?	Current	
	What are the strengths and weaknesses of **emerging** technologies?	Emerging	

	What would be the strengths and weaknesses of **future** technologies?	Future	
Q7	What areas of chemistry could have a major influence on **current** technologies, and to what extent is this influence critical?	Current	
	What areas of chemistry could have a major influence on **emerging** technologies, and to what extent is this influence critical?	Emerging	
	What areas of chemistry could have a major influence on **future** technologies, and to what extent is this influence critical?	Future	
Q8	What support and investment is needed for **current** technologies that will influence the sustainability of the food-supply?	Current	
	What support and investment is needed for **emerging** technologies that will influence the sustainability of the food supply?	Emerging	
	What support and investment might be needed for **future** technologies that will influence the sustainability of the food supply?	Future	
Q9	What recommendations would you give to [any] [all] of the following stakeholders to achieve these objectives?	Government	
		Education	
		Research	
		Industry	
		Learned institutions	
		Others	
Q10	What is the likely consumer perception of the emerging and future technologies?	Answer	
Q11	What impact might major environmental, social and political, legal and economic changes have on these technologies and the sustainability of the food supply? Equally, how might these technologies and the creation of a sustainable food supply create change in these areas?	Environmental	
		Social and political	
		Legal	
		Economic	

Q12	Considering the broad scope of this assessment, which contacts or networks do you think we should approach?	Answer	
General comments			

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