

# Current Trends in Green Technologies in Food Production and Processing

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**Abstract** Finding a balance between food supply and demand in a manner that is sustainable and which ensures the long-term survival of the human species will be one of the most important challenges for humankind in the coming decades. Global population growth in the last several centuries with the attendant demands resulting from industrialization has made the need for food production and processing an important issue. This need is expected to increase in the next half century when the population of the world exceeds 9 billion. Environmental concerns related to food production and processing which require consideration include land use change and tremendous reduction in biodiversity, aquatic eutrophication by nitrogenous and phosphorus substances caused by over-fertilization, climate change, water shortages due to irrigation, ecotoxicity, and human effects of pesticides, among others. This review summarizes key highlights from the recently published book entitled *Green Technologies in Food Production and Processing* which provides a comprehensive summary of the current status of the agriculture and agri-food sectors in regard to environmental sustainability and material and energy stewardship and further provides strategies that can be used by industries to enhance the use of environmentally friendly technologies for food production and processing.

**Keywords** Green technology · Sustainable agriculture · Food production · Food processing · Climate change · Biodiversity

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## Introduction

Food is an integral component of life and human existence. Since the beginning of time, humans have had to eat to survive. In earlier times when human population was much smaller, resources were abundant and there was less need for food processing and storage. As populations grew, limitations in food processing and storage techniques forced more individuals to devote considerable amounts of time daily to feeding themselves and their families (i.e., harvesting and hunting). Industrialization shifted a large percentage of the population toward a myriad of activities creating the need for an industrialized food sector to feed an increasing number of urbanized humans.

Burgeoning population growth in the last several centuries with the attendant demands resulting from industrialization has made the need for sustainable food production and processing technologies even more important. At the same time, changes to climate and population health have made evident the precarious balance between sustainable food production practices, a healthy environment, and a healthy population. In 2050, the population of the world is expected to reach 9 billion FAOSTAT [23]. Adequate supplies of healthy, nutritious food will be needed to maintain global socioeconomic viability. To do this successfully will require that we produce more food with much less impact on our environment. Our ability to meet growing demands for food supplies will, thus, hinge on the sustainability of the practices used in food production and the fervor with which novel processes and technologies are developed to address ever-changing and conflicting pressures.

Since the industrial revolution, worldwide food production has increased significantly but at a slower pace than global population and with much more waste and less efficient resource distribution. Food supply shortages have

left 3 billion people malnourished globally with iron deficiency affecting 2 billion people and protein/calorie deficiencies affecting nearly 800 million people [25]. At the same time, most land and aquatic resources are overused. And even more startling is the estimate that currently 30–50 % of food produced is wasted [4].

Among some of the more serious environmental concerns we face are land use change and extensive reduction in biodiversity, aquatic eutrophication by nitrogenous substances caused by over-fertilization, global warming caused by enteric fermentation and use of fossil fuels, aquatic eutrophication by phosphorous substances caused by fertilizers overuse, water shortages due to irrigation, ecotoxicity, and human effects of pesticides [7].

Growing awareness of these challenges is causing social shifts with some stakeholders including farmers, food manufacturers, consumers, and policy makers, desiring more efficient approaches in agricultural and food production practices. Increasing use of organic inputs in processing, use of recyclable and good-for-the-environment packaging, establishing of just employer–employee relationships, “buy local,” “whole foods,” “free-from,” and “fair-trade” are examples of some of these trends.

Green technology is defined by the global collaborative encyclopedia, Wikipedia, as “the application of one or more of environmental science, green chemistry, environmental monitoring and electronic devices to monitor, model and conserve the natural environment and resources, and to curb the negative impacts of human involvement” (<http://en.wikipedia.org>). In the field of agriculture and agri-food, the term “green growth” is sometimes used and has been defined by the Organization for Economic Co-operation and Development (OECD) as “the pursuit of economic growth and development, while preventing environmental degradation, biodiversity loss and unsustainable natural resource use” [41]. This review summarizes key highlights from the recently published book entitled *Green Technologies in Food Production and Processing* [7]. Issues addressed include key drivers of the evolution in the food supply chain, in-depth description of food production, and processing using the life cycle assessment (LCA) tool; approaches to improve food production practices; sustainable food processing approaches; emerging analytical techniques for sustainable research and development; challenges associated with the use of agricultural resources to grow biofuels and bio-based products; technologies to reduce the generation of process-induced toxins; social factors that influence consumer perceptions about some of the current and emerging agri-food technologies; and the need and importance of biodiversity in maintaining sustainable diets of human populations.

## The Food Chain

Approximately 10,000 years ago, the beginning of agriculture contributed to an intense transformation in the organization of social life, which evolved from the hunter-gatherer and nomadic societal structure to sedentariness. The food chain was very simple—as conservation techniques were limited, foods were grown locally and eaten only when in season. A subsistence agricultural system prevailed, and because of its importance for survival, food was not considered as simply another commodity but an important requirement for existence [28].

The subsistence model was well suited to rural areas or small towns. With the rapid growth of industrialization came larger cities which distanced farmers from urban workers. Retailers appeared as intermediaries between producers and consumers. Urban workers labored long hours to increase their standard of living and consequently demanded more sophisticated foods while having less time for food preparation at home. Food processors were grafted into the food chain to address the gap and provide consumers with partially prepared as well as ready-to-eat (RTE) meals.

During the second half of the twentieth century, key stakeholders in the food chain (producers, processors, distributors, and retailers) increased in size, becoming large industries with a desire to sell large offerings of very specialized products to a global market. This culminated in the signing of the important World Trade Organization multilateral trade agreements in the 1990s. Since then, trade in agricultural products has increased tremendously, from 280 billion US\$ in 1999 to 920 billion US\$ in 2009 [26]. Today, it is not uncommon to have similar products from different countries available at a given grocery store or to have what used to be seasonal produce available all year round because suppliers come from both hemispheres.

A supply chain can be defined as “a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together by a feed-forward flow of material and feedback of information” [51]. The agri-food supply chain in particular refers to a system of actors linked from “farm to fork” to produce consumer-oriented products in a more effective manner and with an optimized flow of agricultural products through the different steps of the chain [28]. The food chain has some specific issues such as (1) seasonality of supply and demand, (2) customer issues of traceability and risk management related to health, nutrition, and safety, and (3) the environmental impact of food production through extensive resource use, including water and land use and from the significant greenhouse gas emissions and waste resulting from agricultural production [36].

It is not surprising that the food chain has become more complex as the income of the average population has risen. Low-income populations eat what they can afford but, as a population gets wealthier, the criteria for food selection increases and food choice is increasingly affected by factors such as food safety, good taste, long shelf life, non-GMO, and additional health benefits. Table 1 summarizes the main differences in the supply chain of low-, medium-, and high-income countries.

A significant trend in the structure of agri-food supply chains is the growing concentration and consolidation that has taken place at all levels of the chain. This concentration is a concern if it results in collusion, price fixing, and unfair market practices. Competition policy exists in most developed countries but there is no doubt that the activities controlled by large firms may have significant implications for the structure and management of the supply chain [36].

At the farm level, the race for higher productivities has resulted in the use of bioengineered varieties and more sophisticated inputs (e.g., machinery, fertilizers, and pesticides). In some instances, the monopoly of the seed

supply has generated monocultures of only one variety which can have a large impact on biodiversity.

Primary producers, food processors, and retailers are under constant pressure from domestic and international markets to improve efficiency of their operations and reduce costs while satisfying customers. Most large companies have introduced into their quality control systems some form of traceability not only internally but also with suppliers. This includes not only product quality and safety but also some environmental considerations such as energy reduction, water issues, waste reduction, packaging reduction, greenhouse gas (GHG) emission, transportation, sustainable agriculture, renewable energy, and carbon footprint. Nestlé and Wal-Mart are two examples of such companies with a large enough market share to have substantial impacts on the sector.

### Life Cycle/Environmental Impact Assessment

Since the Industrial Revolution, humanity has been living under increasing environmental credit: natural resources are shrinking exponentially while wastes are accumulating globally at near parallel rates. Not surprisingly, since the 1970s, there has been a growing outcry about the danger of human activities to its own survival. And yet, today, questions about how to do things differently remain. The apparent immediate solution is the establishment of mitigation measures but, more often than not, these measures simply move the pollution from one place to another (e.g., gas scrubbing).

At the Rio Summit in 1992, sustainable development was defined as: "...development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [11]. For this to be of practical use, tools are needed to measure and compare the environmental impacts of various human activities relative to "sustainable standards."

### LCA of the Food Sector

Life Cycle Assessment (LCA) may be defined as a product-oriented environmental tool which provides a systematic way to quantify the environmental effects of individual products or services from cradle to grave [32]. LCA starts by defining an activity (product or service) and decomposing it into a sequence of sub-processes that use resources to produce (a) desired products, (b) by-products, and (c) unwanted outputs (wastes). By subdividing sub-processes into their smallest elements, it becomes possible to track and tally (embed) the resources used and the unwanted outputs of each elemental sub-process into the

**Table 1** Main characteristics in the supply chain for low-, medium-, and high-income countries

Constituents of the food supply chain	Traditional agriculture	Modernizing agriculture	Industrialized agriculture
Inputs intensity	Low input use	High level of use	Enhanced input use efficiency
Primary agriculture	Diversified	Specialization of cropping systems	Specialization and focus on conservation
Processing sector	Very limited	Processed products are seen as value-added and provide employment	Large processing sectors for domestic and export markets
Wholesalers	Traditional wholesalers with retailers bypassing for exports	Traditional and specialized wholesalers	Specialized wholesalers and distribution centers
Retailers	Small market	Spread of supermarkets, less penetration for fruits and vegetables	Widespread supermarkets.
Consumers	Rising caloric intake	Diet diversification, switch to processed foods	High value, processed foods.
Traceability	No traceability	In some chains with private standards	HACCP programs

Source: [26]

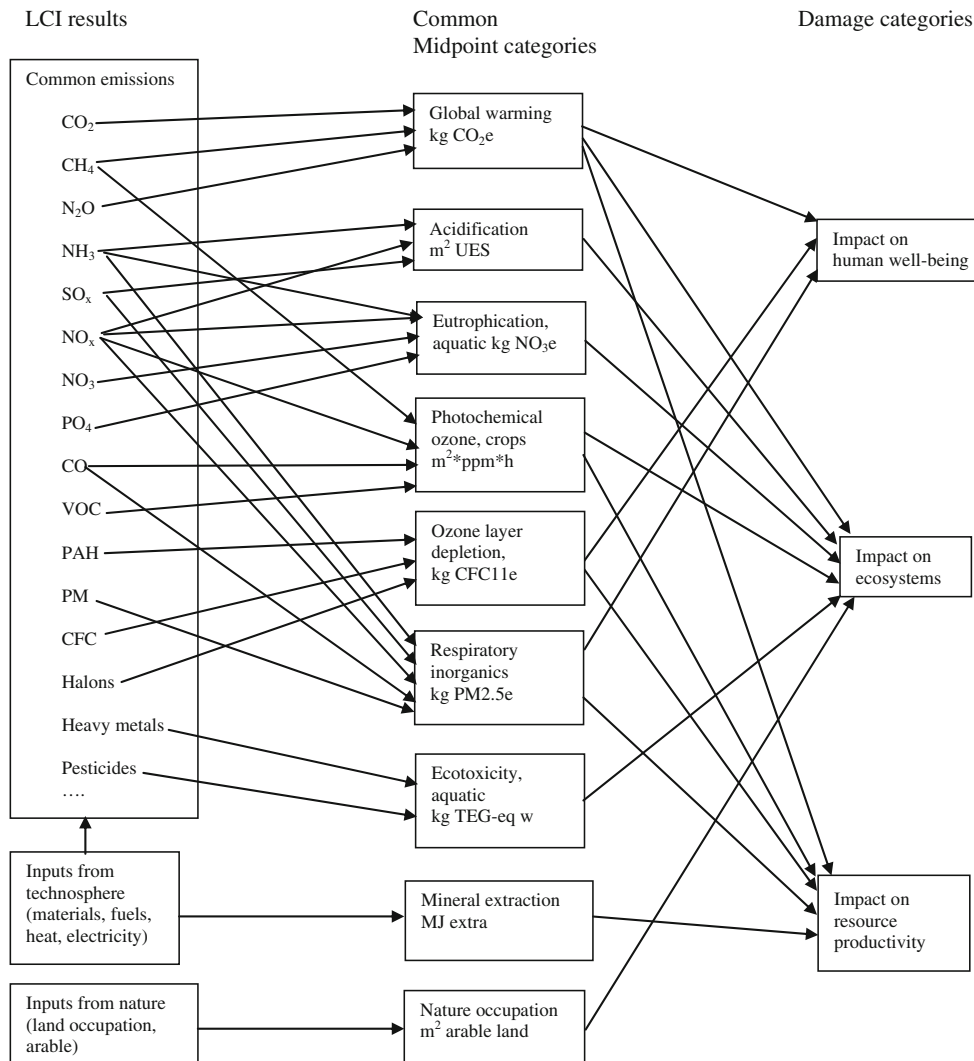
complete product (or service) under examination. This is called the Life Cycle Inventory (LCI).

The next step, which is the Life Cycle Impact Assessment (LCIA), estimates the impacts of resource depletion and waste generation using a series of models. The main strength of LCA is that it tries to have a holistic view of the activity under study by taking all impacts into account and fusing all models into one coherent model. Figure 1 shows one such supra-model. As shown, production of one portion of meat from beef generates a variety of emissions. The model shows numerous midpoint impacts and thus illustrates how this activity can alter resource productivity, ecosystems, and human well-being.

In LCA, final impact results are easier to interpret than midpoint impacts. But, conversely, the accuracy of the final results is weaker because the uncertainty associated with the inventory data is increased by the uncertainty of the different impact models. LCA is, nevertheless, now well

recognized internationally and has its own ISO standards which define the general methodology, variants, and accuracy of the different results (ISO 14 040–14 049, European Commission—Joint Research Centre—Institute for Environment and Sustainability [17]. As indicated in the ISO standards, conclusions depend strongly on the chosen assumptions. First and foremost is the choice of the type of LCA (attributional vs consequential). The attributional approach describes the resource use and emissions that have occurred to produce the product in question, whereas the consequential approach accounts for the resource use and associated emissions that arise to replenish stocks of the product that have been used [32].

Another set of assumptions comes from the definition of the functional unit and the boundaries of the system under study. An example of an ill-defined functional unit is “1 kg of beef meat packaged at the retail store in Toronto.” A well-defined functional unit will, at least, say which race of



**Fig. 1** General structure of an LCA model linking inputs and outputs of inventory to midpoint and final impacts. *Source:* [32]

beef, where it was raised, what its diet was, age of animal when killed, how and where it was slaughtered, how it was transported, what kind of packaging was used, and so on. Moreover, allocations are often necessary to adequately associate specific emissions to different products and by-products. For example, cows provide milk (during their life) and meat (upon slaughter). This raises the question of which proportion of the methane produced every day should be attributed to each liter of milk versus each kg of meat produced. General rules in setting these assumptions are constantly revised to ease the comparison between different LCA results.

LCA is a generic tool that is adaptable to any situation and which is evolving quickly. The impact of land availability, as an example, has been added as a resource to get a fair comparison between intensive and extensive agriculture. Intensive agriculture uses more fertilizers, whereas extensive agriculture has larger impacts on deforestation and loss of biodiversity. Modeling of these resources and impacts is in its infancy and is changing rapidly.

### LCA of Food from Plant Origin

The compatibility of agricultural productivity and sustainability is an important socioeconomic question [10]. Foods of plant origin (e.g., fruits, vegetables, and cereals) are produced through gathering either from natural habitats or from man-made plantations. Man-made cultures started over 10,000 years ago when populations increased to the point where gathering within walking distance became impossible. Today, human populations have reached a point where large proportions of the world's natural habitats have been transformed for agriculture. Between the years 2000 and 2030, the world population is projected to increase by 40 %, cereal production by 50 % (due to improved standard of living in certain countries), whereas arable land is expected to increase by only 7 % FAO [20, 21]. This will require agriculture to be more efficient (more intensive) which will put more pressure on rural areas. Plants need minerals, which come from the soil, to grow. To ensure productivity and profitability, minerals have to be added in slight excess without affecting the surroundings. LCA provides a suitable tool to quantify the resources needed, the wastes generated, and the impacts of agricultural activities. Numerous studies have shown the significant effect of nitrogen and phosphorus fertilization on eutrophication, acidification, global warming, and photochemical ozone. Additionally, particulate formation (dusts), loss of biodiversity caused by land use change, toxicity, and depletion of abiotic resource (it takes crude oil to produce the fertilizers) have raised concerns [10].

For crops, a functional unit is generally considered as a ton of grain ready to leave the farm. Contrary to other

sectors, agricultural production often takes place within an open space (i.e., without distinct borderlines for soil, water, and air) and with uncontrolled conditions (temperature, rainfall, extreme weather). This adds a considerable amount of uncertainty to nutrient runoff or volatilization measurements or estimations for modeling which can change the conclusion of any LCA tremendously. This explains why recent studies tend to use average multiyear values under standardized conditions [5, 8, 53].

Another specific element of many agricultural LCIs is the need for land use data. Former quantification data sets were limited to the area used per functional unit but more recent studies tend to add the quality of the original area into account as transforming a desert into agricultural land does not have the same impact as using a rainforest for the same purpose Brentrup et al. [9]. Besides these direct effects, indirect land use impact may also be of relevance (e.g., if the cultivation of bioenergy crops displaces food crops to other areas).

### LCA of Food of Animal Origin

The world population increased exponentially to reach 7 billion in 2011 and the majority of the projected increase to 9 billion by 2045 is expected to come from Asia and Africa FAOSTAT [23]. At the same time, rural populations are decreasing in every region of the world to the point where some rural populations may disappear in the next 30 years. Global growth rates of animal product consumption (meat, milk and eggs) per capita is higher in wealthier countries and increases more rapidly in countries with higher economic growth rates FAO [22]. Although there are differences between regions, meat consumption per capita will globally increase by 7 % in developed countries, 33 % in Latin America, 65 % in the Middle East and North Africa, 82 % in Eastern, Asia and 100 % in sub-Saharan Africa. To meet this growing demand, animal herd has increased by a factor of 2, 2.5, and 5 for beef, swine, and poultry, respectively FAOSTAT [23]. For proteins derived from sea products, the catch has increased 6.5-fold in the last 50 years WHO/FAO [59].

Livestock production systems have evolved in past decades due to increasing demand for animal protein, on one hand, and economic growth rates and technical innovations, on the other. Over time, local family farms were sold or transformed into sophisticated high production factories. This led to the adoption of high-energy diets, genetic improvements, high-density animal concentrations, and the use of growth hormones and antibiotics. Globalization also concentrated these animal factories in areas where the economics are favorable without due consideration of sustainability.

LCA of animal production involves mainly feed, water, and land use. Water and land use for the sole production of the animal is not very important but the water and land use embodied into the production of feeds are significantly more important, leading to two different production systems: extensive and intensive [56]. In extensive production systems, farmers produce the feed needed locally. The number of animals in such systems is restricted in order not to exceed the grass or crop feed capacity of the land and in so doing minimize the risk of soil degradation [14, 16, 60] or deforestation [18, 19]. In intensive production systems, animals are more densely packed into barns and the feed is purchased from specialized companies preparing high-energy rations from grains that may be located anywhere in the world. This “distanciation” between crop and manure production forces the injection of fertilizers to the crop land and the disposal of excess manure to nearby fields which could lead to water and air pollution [37].

Moreover, the use of cereals for animal feeding represents about half of global cereal supply [39]. As the land required for one portion of animal protein can give close to 10 portions of plant proteins, it is not surprising that the land used for animal feeding has become an important issue.

Animal production affects biodiversity in a variety of ways including through (a) soil degradation in overused extensive systems, (b) land use change to crop monocultures, and (c) animal selection [2]. Furthermore, the effect of animal production on global warming has become a matter of increasing concern. Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) are the three main contributors to GHG emissions. They come mainly from enteric fermentation, from manure and fertilizers degradation as well as in association with biological nitrogen fixation in pulse and legume crops [56]. The global warming potential of methane and nitrous oxide is about 20 and 300 times the potential of carbon dioxide. In 2005, global agriculture was estimated to account for about 11 % of all anthropogenic GHG emissions. The agricultural share of total anthropogenic CH<sub>4</sub> and N<sub>2</sub>O emissions was about 47 and 58 %, respectively [49]. Water required for animal production is generally higher than that required for crops because the direct water consumed by the animal and the water used to produce its feed have to be taken into account [50]. The world average water footprint per kg of meat was estimated at 15,500 L for beef, 6,100 L for sheep, 4,800 L for pork, and 3,900 L for poultry [33]. Water runoff from animal production may also be of concern because of its high capacity to pollute receiving water surface or groundwater [35].

Vergé et al. [56] in reviewing the production of milk, beef, pork, poultry, and aquaculture and their impacts on global warming concluded that comparing results of LCAs is very difficult because of the different assumptions in the

type of LCA, the functional unit, the system boundaries, and method of allocation chosen. Notwithstanding these differences, studies indicate a net positive impact of mitigation practices and beneficial management practices.

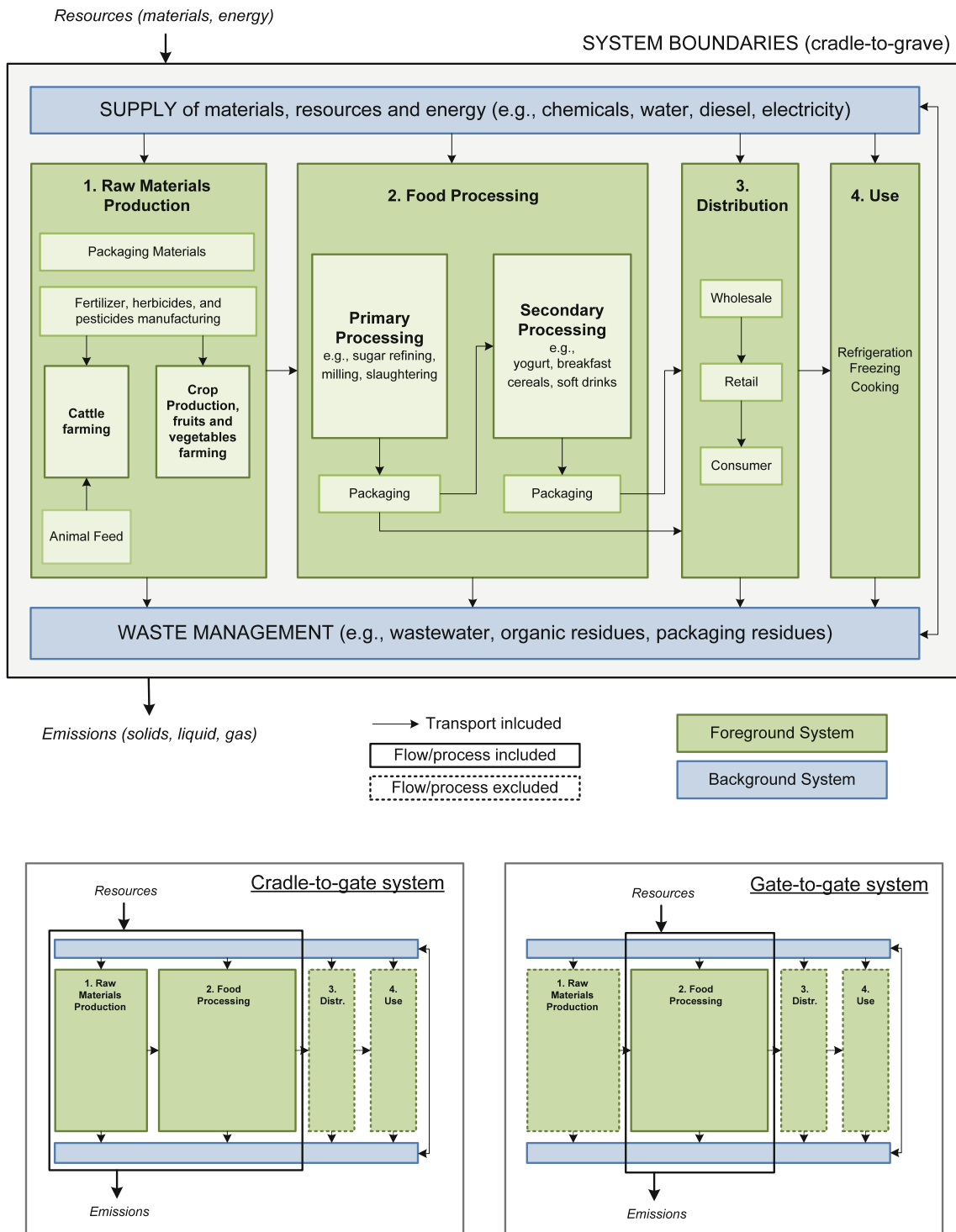
### LCA of food processing

It is generally accepted that the most important “contributors” to the non-sustainability of food production (i.e., along the whole food chain) are pesticide overuse, food processing, packaging, and extensive transportation of imported goods. Extending the LCA to include food processors therefore seems judicious. In fact, the first “LCA inspired” studies date back to the 1960s and come from food processors [34] analyzing the effect of different packaging (glass vs. plastic soda bottles and polystyrene foam vs. paper pulp meat trays).

Food processing is a diversified sector encompassing the use of various raw materials, processes, and end products. It ranges from minimal (e.g., selling fresh carrots) to very complex (e.g., carrots that are washed, cut, and packaged to be sold to food processors making sauces and stews who sell to caterers preparing individual sized meals to be sold to supermarkets or for airline catering).

LCA of processors are “extensions” of cradle-to-farm-gate LCAs (Fig. 2). Boundary expansion is generally easy to do because the boundary for food processing extends only as far as the physical limit of the manufacturing facility. However, the processor’s functional unit is generally very different from the farmer’s which leads to difficulty in allocations. A simple example is the proportion of the GHG produced by a cow (farmer’s functional unit) that should go to each hectoliter of milk sold (dairy processor unit) versus to the carcass sold (meat processor unit)? A more complex example would be to assess how much GHG can be tagged to a meal of beef stew eaten with a sauce containing milk solids and a cream based dessert?

Raw materials used in the food and drink industry are of agricultural origin and are made from limited resources of land, water, and energy and produced using manufactured inputs such as fertilizers, pesticides, and cleaning agents. Environmental issues related to the food processing chain mainly include reduction in biodiversity (i.e., through land use change and monocultures); wastewater generation (including biological oxygen demand) and nitrogen, phosphorus, and sulfur availability; particles and toxicity; and generation of packaging wastes and organic residues (including by-products production) as well as air pollutants emissions (i.e., volatile organic compounds, particulate matter, greenhouses gases, odors, and refrigerant leaks). Non-environmental issues include diet simplification, animal welfare, workers’ conditions, and the generation of acceptable social and economic



**Fig. 2** System boundaries for food LCA study. Cradle-to-grave (top), cradle-to-gate (bottom left), and gate-to-gate (bottom right) system boundaries. Source: [3]

conditions. The relative importance of these factors depends strongly on the food sector and the stakeholder within the food chain but, in general, food processing has lower environmental impacts than farming [3]. Either because they are forced to by legislations or as a direct result of their own

initiatives, an increasing number of food processors are evaluating their business activities in order to report, improve, and/or market their environmental efforts including their supply chain. Proactive initiatives are driven, on one hand, by the positive image processors and retailers can convey to

purchasers and consumers. On the other hand, performing an LCA reveals potential areas to reduce inputs, energy, and water which has cost savings advantages and consequent environmental benefits.

### LCA of Transportation Along the Food Chain

As food products often travel long distances to reach consumers, one might expect transportation to be the major food-related contributor to greenhouse gas emissions in many developed countries. In fact, almost half of the fruits consumed in North America is imported and domestic grown produce travel an average of 2,000 km from source to point of sale, not infrequently via air [42]. Movement of food is done through a highly complex, relatively integrated industry sector including ships, trains, trucks, planes, and warehouses and often require special packaging [57]. Food supply chains are especially challenging because of seasonality, freshness, spoilage, and sanitary considerations.

Weber and Matthews [58] showed that international water shipments have the lowest GHG impact closely followed by inland water and rail; trucking produces 10 times more GHG per ton-km travelled, whereas air transportation is 40 times higher. Unfortunately, faster modes of transport produce more GHG per ton-km. Consequently, the impact of transportation depends on the type of transportation mode, the delay from source to consumer and the transportation conditions (i.e., temperature, special atmosphere, and frailness). Most LCA studies present results of transportation as a percentage of the impact of the total food chain. Depending on products and processes, the impact of transportation on GHG ranges from less than 5 % to more than 50 % (lower percentage values are generally found with products already embedding large GHG from farming and processing (e.g., milk powder)).

### Green Technologies in Food Production

Green food production often evokes organic farming practices typical of a few centuries ago. This type of farming uses a small area of land for crops and another dedicated area for grazing beef, sheep, and goat. Farm entities were almost always self-sufficient with no use of pesticides or herbicides and the only fertilizer used was manure. As a typical cradle-to-cradle approach, organic farming suits the notion of a green technology. As bucolic as the image is, these farming practices have to be evaluated for sustainability. A generally valid quantification of the environmental performance of organic agriculture is, however, difficult as there is high variability between countries, regions, farm types, and products. Furthermore,

different assessment methods lead to partly contradicting conclusions on the environmental impacts of organic farming. Organic farming performs better in terms of biodiversity, soil fertility, air quality, mitigating resource depletion and climate change, and groundwater pollution as compared to conventional agriculture [44]. However, there are specific environmental impacts against which organic agriculture performs no better than conventional farming (Fig. 3).

A more specific aspect of green food production is the management of nitrogen and phosphorus. These nutrients are taken up from the soil by crops and returned partially through manure management. In intensive production, these nutrients rapidly become the growth limiting factor. Fertilizers must be applied in slight excess to be certain crops will not be growth limited. In highly specialized production food systems, crop growers do not own animals and thus manure is not readily available. Crop producers must rely on external inputs of fast release mineral nutrients. These products undergo numerous chemical transformations depending on the type of soil, type of crop, period of the year, and the immediate weather. Unfortunately, this often leads to nitrogen volatilization and nitrogen and phosphorus runoff during rainy weather. On the other hand, concentration of animal production produces a surplus of manure requiring disposal. This often results in manure overspreading which leads to odors and nutrients percolating into the aquifer or runoff into surface water. Correctly managing the nitrogen and phosphorus agronomic cycles can help regain soil fertility and minimize pollution. Vayssières and Rufino [55] developed a detailed model of the nitrogen cycle on farm of different farming management practices and showed that the sources of nitrogen losses within the nutrient cycle in agro-ecosystems are numerous and the losses substantial. As an example, estimates suggest that about 15 % of N used in mineral fertilizers and 30 % of N excreted by domestic animals worldwide are globally lost in the form of harmful gases (NH<sub>3</sub> and N<sub>2</sub>O). A holistic approach along the production value chain is needed to manage these losses and minimize negative impacts.

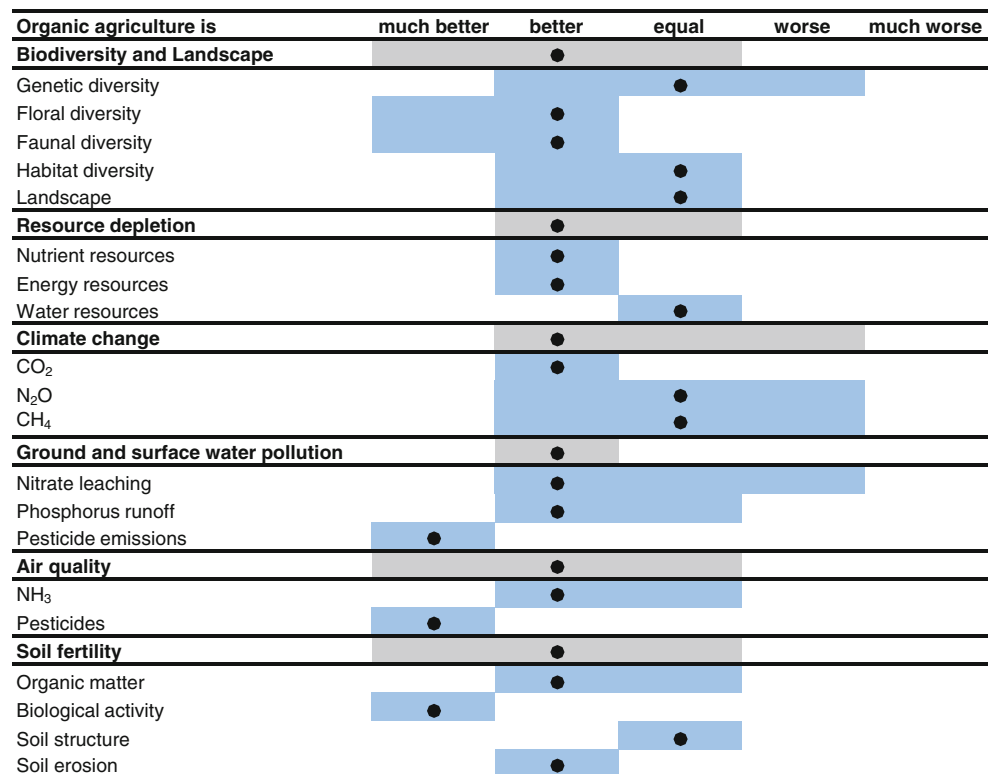
As most of the demand for food products in the near future will come from Africa and southeast Asia, it is important to identify affordable management practices for these countries. With a well-chosen combination of technical options, N-use efficiency can be substantially improved in farming systems of both developing and industrialized countries.

### Green Technologies in Food Processing

Foods must frequently be processed to ensure safety and increase shelf life, quality, and nutritional properties while making them more convenient. Primary, secondary, and



**Fig. 3** Classification of environmental impacts and relative performance of organic farming compared to conventional farming *Source:* Schader et al. [44]



based on Stolze et al. [52], adapted

tertiary processing techniques are explored to transform raw produce into value-added foods and ingredients. Primary processing techniques such as cleaning, sorting, grading, dehulling, and milling are used as a first step in the processing of most grains. In the animal sector, primary processing includes but is not limited to, candling and harvesting of eggs; deheading, gutting, filleting, scaling, washing, chilling, freezing, or packing of fish; storage, separation, homogenization, and pasteurization of milk; slaughter, dressing, boning, acidification, salting, brining, smoking, thermal processing, refrigeration, and storage of meat. Secondary and tertiary processing techniques are further applied to transform these foods into other value-added food products.

One of the most promising technological approaches to reduce environmental footprint in food processing is the use of enzymes. As biological catalysts, enzymes speed up reaction rates and in so doing offer savings in terms of time, energy, and cost. Food enzymes provide advantages in terms of specificity, sensitivity, their relative non-toxicity, high activity at low concentrations, and ease of inactivation. Enzymatic approaches entail milder treatments and/or mild reaction conditions, thus are more environmental friendly and would protect the environment better compared to traditional methods [48]. Furthermore, the discriminatory nature of enzymes in terms of the specificity of molecules they act on as substrates results in more uniform and more consistent products. In addition to environmental benefits, the action of

enzymes in foods may result in products with extended shelf life, improved textures, appearance, flavors, functionality, and yield, enabling a variety of food products to be fabricated from harvested produce [48]. Examples of enzymes that can be used in food processing include carbohydrases (e.g., amylases, pectinases, cellulases, galactosidases, and chitinases); lipases (e.g., pancreatic lipase and phospholipases); proteases (e.g., pepsins, trypsins, bromelain, papain, amylases, and cellulases); isomerases (e.g., glucose isomerase); transferases (e.g., transglutaminases); and oxidoreductases (e.g., glucose oxidase and polyphenol oxidase).

Trends in enzyme-assisted food production include enzyme engineering aimed at developing enzymes with superior activities which can be used under mild processing conditions (e.g., nonthermal food processing operations) or which can resist extreme conditions of pH, temperature, and pressure encountered during food processing. Technologies for increasing the yield and storage stability of these enzymes are also of interest. Furthermore, opportunities exist in engineering design to develop application formats that enhance ease of use, recovery, and reuse.

Another priority concern in food processing is food safety. Thermal treatments such as pasteurization, sterilization, aseptic processing, refrigeration, and chemical preservatives have been traditionally used to decrease microbial loads in foods and to enhance safety and shelf life. As many of these operations are energy intensive,

**Table 2** Emerging technologies for microbial control in food processing

Technologies	Examples
A) Biopreservation	Bacteriocins Organic acids Probiotics
B) Electromagnetic wave heating	Microwave technology Radiofrequency technology
C) Electric and magnetic fields	Ohmic heating Moderate electric field heating Inductive heating
D) Nonthermal technologies	Pulsed electric field High pressure processing Ionizing radiation Ultraviolet radiation High-intensity pulsed light Ultrasound Ozonization Cold plasma processing

Source: [40]

alternative techniques that require less energy and that have less environmental impacts should be considered. Novel and innovative methods of microbial control in food processing include microwave and radio-frequency heating (MW/RF), pulsed electric fields (PEF), high pressure processing (HPP), ionizing radiation, ohmic heating (OH), treatment with ultraviolet light, and ozonisation [40]. Table 2 provides a list of some of the alternative techniques that could be considered for microbial control.

Drying, which represents a significant cost investment and a major source of energy consumption for most companies, is another important unit operation that must be considered when a greener process is targeted. Drying is a critical unit operation in the processing of many bulk and packaged food products and ingredients. It is used to provide texture, enhance shelf life, and decrease transportation costs. The typical elements of a drying operation include wet feed pre-treatment, drying, retrieval of dried product, and heat recovery from exhaust gases. To reduce energy consumption, elimination of the drying operation from the production process altogether, or its replacement with lower-energy consuming operations, should be envisaged [29]. Furthermore, whenever possible, initial moisture content of the wet feed to be processed should be reduced using less energy-intensive techniques such as pressing, membrane separation, filtration, centrifugation, coagulation, and sedimentation, prior to the drying process. As an example, osmotic dehydration can be considered as a pre-heat treatment unit operation or a final dehydration step [30].

Preheating of wet feed to as high a temperature as possible using energy-efficient means can also help to

reduce overall energy use. Additionally, utilization of environmentally friendly energy sources and energy-efficient drying installations and maximal use or recycling of different waste streams and by-products are useful considerations [29]. Furthermore, to reduce or eliminate environmental pollution, efficient installations which can completely recover energy, particulates, and greenhouse gases from exhaust gases must be considered.

The typical elements of a green drying installation scheme are presented in Fig. 4. To reduce energy use and environmental impacts, heat is recovered from exhaust gases and is recirculated in the drying operation. Exhaust gases after heat recovery can be further scrubbed to remove greenhouse gases. Whether for drying or for other unit operations, the type of energy source used in food processing can have an impact on the total amount of energy consumed and the environmental footprint.

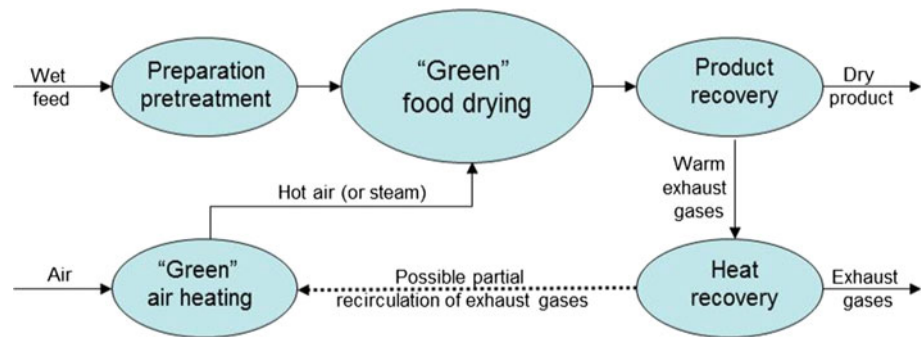
There is general understanding of the need to move from carbon-based energy sources to solar, hydroelectric, and wind. Generally, solar and wind energy sources are natural, abundant, and considered clean and environment-friendly as they create no, or minimal, greenhouse gases. Hydroelectricity is considered by some to be not as environmentally friendly as solar or wind because it involves flooding large area of land which produces methane through anaerobic degradation of the organic material flooded for decades. Debate continues over the safety of nuclear energy and further considerations are needed on the risks versus benefits in terms of health and environmental impacts. A comparison of the energy and thermal efficiency of selected industrial dryers is provided in Table 3.

A final unit operation in many food processing plants prior to storage and distribution is packaging. This is an important activity that has impacts on product acceptability, choice, safety, and nutritional quality. Packaging also provides a means of communication with consumers and allows foods to be portioned in convenient formats. Under-packaging puts foods at risk, whereas over-packaging has high environmental footprint. Greener packaging design considerations should include the maintenance of required functionality, material use minimization, increasing recycled content and use of recyclable materials, and avoidance of potentially toxic constituents [46]. As for other operations, LCA could be a useful tool to evaluate the benefits and disadvantages of alternative packaging systems.

### Reducing Process-Induced Toxins in Foods

Many food processing treatments use high temperatures and sometimes pressures (e.g., extrusion cooking) which can generate process-induced toxins. Examples of toxic compounds of concern in foods include nitrosamines,

**Fig. 4** Typical elements of a “green” drying installation scheme. *Source:* [29]



**Table 3** Energy and thermal efficiency of selected industrial dryers

Method or dryer type	Energy or thermal efficiency (%)
Tray, batch	85
Tunnel	35–40
Spray	50
Tower	20–40
Flash	50–75
Conveyor	40–60
Fluidized bed, standard	40–80
Vibrated fluidized bed	56–80
Pulsed fluidized bed	65–80
Sheeting	50–90
Drum, indirect heating	85
Rotary, indirect heating	75–90
Rotary, direct heated	40–70
Cylinder dryer	90–92
Vacuum rotary	Up to 70
Infrared	30–60
Dielectric	60
Freeze	10 or lower

*Source:* [29]

heterocyclic aromatic amines, acrylamide, furans, polyaromatic hydrocarbons, and bisphenol [1]. In addition to reducing the environmental footprint and the use of chemical additives, green technologies in food processing should aim to limit the levels of toxins in foods.

Formation of process-induced toxins and their levels in foods is frequently dependent on the levels of their precursors in foods as well as processing conditions (e.g., method of cooking, duration, and temperature). Formulation (i.e., ingredient selection), breeding (e.g., potatoes with low levels of asparagine and sugars to decrease acrylamide content in foods), and use of modified cooking conditions and/or alternative cooking methods (e.g., microwave) are examples of approaches that could be considered to minimize the generation of process-induced toxins. Transfer of toxic chemicals from food processing utensils and containers (e.g., BPA and phthalates used in modern plastics) can also occur; thus, appropriate

equipment and material selection must be done to avoid the inadvertent presence of these chemicals in foods.

As consumers become increasingly aware of the nutritional quality of the foods they consume, national and international regulatory agencies will need to keep pace through the development of rapid and sensitive detection methods and generation of evidence-based data to assist in the establishment of tolerance and safe levels of chemical toxins in foods.

### Waste Reduction Along the Food Supply Chain

Paradoxically, superior plants and animals have evolved to have the least efficient nutritious cycle possible. Strangely, this is one of nature’s successes as it promotes biodiversity. As an example, when a bird eats a cherry, it will most probably take just a few bites and leave the rest including the stone. When the bird is killed by another animal, the predator feeds a lot less than its subsequent predator and when humans kill the predator, they also feed on a fraction and excrete a non-digestible “waste.” All the remains serve as food to other species such as animals, insects, microorganisms, and finally other plants. Thus, nature recycles its main building blocks and permits evolution.

As the human race has mastered agriculture, a large portion of food is thrown away through farming, processing, distribution, retail, consumption, and excretion. Feeding the world, therefore, generates a tremendous amount of waste. Fortunately, most of the waste is biodegradable and is easily incorporated into other nutrient cycles.

Humans discovered quite early that wastes from plants and animals can cause serious diseases and as a result disposed of them in recessed areas or buried them in pits. This was the first efficient waste disposal approach. With the explosion of the human population, food production and processing has become intensive and the amount of waste generated is less easy to dispose of, especially in urbanized communities. Wastes therefore have to be minimized and processed properly throughout the entire food chain in order to ensure the sustainability of the sector.

**Table 4** Weight proportion of waste, by type, arising from UK food and beverage supply chain from processor to the consumer

Supply chain stage	Food (%)	Packaging (%)	Other (%)	Total (%)
Manufacturing	6.6	1.0	5.2	12.8
Distribution	0.01	0.22	0.02	0.3
Retail	0.9	2.7	0.1	3.7
Household	21.3	9.2	52.7	83.2
Total	29	13	58	100

Source: [www.wrap.org.uk](http://www.wrap.org.uk), 2012

Wastes occur across the food chain, and while some waste generation may be avoidable, others are not. For example, of the entire corn plant, only the grains are eaten as food; unfortunately, over 95 % waste is unavoidably generated in the process. Although plant breeding techniques have succeeded in creating plants with larger quantities of edible parts and genetic engineering promises to push this further, mankind will never be able to eat 100 % of all the plants and animals we feed on. Other wastes, on the other hand, are avoidable. Examples include, the choice to eat parts of plants and animals we are culturally not used to consuming; accepting to buy “less than perfect” fruits and vegetables; managing food reserves in such a way that we buy and prepare just what we need on a per meal basis.

Food is an important part of human wastes. Data from the UK food and beverage supply chain from the processor to the consumer shows that approximately 40 % (by weight) of all solid wastes involve food and its packaging (Table 4). The table also shows that over 80 % of all wastes come from the consumer. Food waste prevention is a multilevel hierarchy process inspired from the 3RVE (i.e., reduce, reuse, recycle, valorize, and eliminate) waste reduction strategy. One should first try to REDUCE as much as possible and then try to REUSE, and after that try to RECYCLE, then VALORIZE, and if nothing else works, ELIMINATE. The United States Environmental Protection

Agency (USEPA) has proposed the hierarchical solution presented in Table 5.

Source reduction starts at the consumer level focusing on behaviors at home and in the hospitality industry (i.e., restaurants, hotels, and catering services). As change in the way customers behave at home may be very difficult, one of the few potential solutions is through education. This may involve learning how to plan meals, cooking just enough, not overfilling our plates, and better recipes to cook leftovers and not so fresh food material. Whereas numerous small initiatives exist for the reduction and reuse of food in the hospitality industry, these are often limited due to fears of lawsuits for poisoning attempts and food safety risks.

Reduction in wastes at the retail level should include initiatives to market different grades of fresh produce or outdated material at different price levels. Initiatives at the wholesale and distribution level should involve just in time victualing and appropriate packaging and temperature control to minimize losses, although these latter two are not important contributors (see Table 4). The Table also shows that food processors are the second largest contributor to food waste. As much of the wastes are neither food nor packaging, the potential for food reduction is not high. Nevertheless, process audits can often lead to optimization which could help in identifying plant specific solutions.

Waste treatment is used when food waste disposal is unavoidable. As most wastes are solid in nature, there are two principal methods available: landfilling and incineration. Landfilling has been used for centuries and is still the cheapest method (although prices are rising rapidly). This solution, however, requires large land areas and may contribute to the production of greenhouse gases (mainly from methane generation) as the food decomposes anaerobically. This method is suitable for both rich and poor countries. Burning of food waste requires a much smaller area for the incinerator as well as for burying the residues (which are more stable). However, this method can release toxic substances into the air.

**Table 5** United States Environmental Protection Agency (USEPA) food recovery hierarchy

Hierarchy of action	Example of action
1-Source reduction	Reduce the amount of food waste being generated
2-Feeding people	Donation of excess food to food banks, shelters
3-Feeding animals	Provide food scraps to farmers
4-Industrial uses	Provision of fats for rendering, oil for fuel, food discards for animal feed production; anaerobic digestion with soil amendment or composting of the residues
5-Composting	Aerobic digestion of food scraps into a nutrient rich soil amendment
6-Landfill/Incineration	As last resort

Source: [www.epa.gov/osw/conserves/materials/organics/food/fd-gener.htm#food-hier](http://www.epa.gov/osw/conserves/materials/organics/food/fd-gener.htm#food-hier)

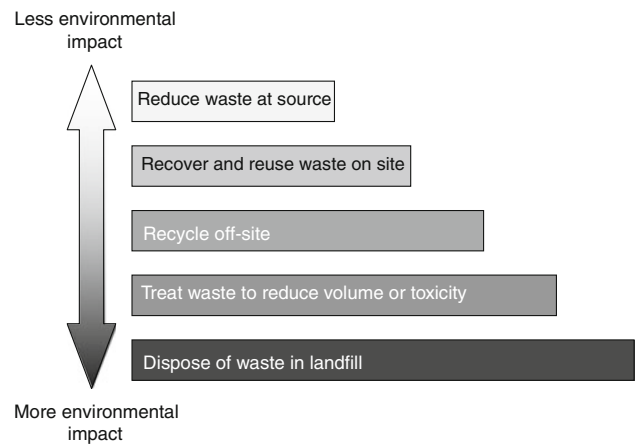
At all stages of the food chain, wastes also appear as suspended or soluble material in water. These can be treated by numerous variants of aerobic or anaerobic wastewater treatment processes. Essentially, these treatments first remove the particulate material using filtration and sedimentation and then treat the soluble material (and fine organic particles) by contacting the liquid waste with aerobic or anaerobic microorganisms. Pollution is removed from the water and “transferred” into biomass surpluses that are treated with the filtered and settled particulate matter as organic solid wastes. Variants of wastewater treatment plants exist for rich and poor countries. Their effectiveness in pollution removal is generally better in richer countries.

Gaseous nuisances are generally not treated in poorer countries as current technologies are quite expensive. These technologies rely on absorption or adsorption onto a solid or liquid substance sometimes with the aid of microorganisms. Some expensive substrates are regenerated (e.g., activated carbon) while other are cheap and can be discarded with the solid wastes (e.g., sphagnum peat biofilters).

### Greening Research and Development

The development of successful food production and processing practices is anchored on good science. Research and development (R&D) are key components of the innovation continuum and in most cases is the area where the majority of funds are spent in the initial stages of process design and product development. The agricultural and agri-food sectors in particular have relied heavily on R&D to increase crop yields, decrease the need for high agricultural inputs, identify faster methods to detect pathogens, conserve foods to prevent spoilage, and identify compounds in foods with health-promoting properties, to name a few examples [6]. Activities undertaken as part of R&D efforts can have environmental impacts; thus, greening of the food production and processing sectors requires a careful look at the inputs into R&D in order to identify areas that can be targeted to reduce environmental footprints while enhancing economic benefits and speeding access to markets.

Energy and water use per square foot in many laboratory buildings are several times higher than in regular office buildings. Similarly, research and chemical laboratories use markedly larger quantities of hazardous chemicals and generate significant waste. As with food processing installations, many of these facilities contain high numbers of containment and exhaust devices and heat-generating equipment which must be accessible continuously and, therefore, require constant maintenance and non-interrupted power supply.



**Fig. 5** The waste management hierarchy. *Source:* [6]

Revolutions in information technology in the last two decades have provided tremendous opportunities to make R&D greener. A paradigm shift in the approaches used for experimentation has, however, been required which has made progress slow. Novel approaches worth considering include micro- and nanoscale chemistry, use of open innovation which capitalizes on networked intelligence, and adherence to concepts promoted in the waste management hierarchy presented in Fig. 5 which provides a path to minimize resource use and reduce waste. Some of these are briefly discussed below.

Microscale chemistry is an environmentally safe pollution prevention method of performing chemical processes using small quantities of chemicals without compromising the quality and standard of chemical applications in education and industry ([www.microscale.org](http://www.microscale.org)). The approach focuses on extensive reduction in the amounts of chemicals used during experimentation and further promotes the use of safe and easy-to-manipulate techniques and miniature laboratory ware allowing a decrease in chemical use by several orders of magnitude [6]. More recently, advances in nanotechnology have further expanded the possibility to miniaturise both research and development in ways that were hitherto inconceivable. Micro- and nanotechnologies are being explored in food quality, food safety, packaging, and health and nutrition research [38]. However, technological advancements in equipment design and new platforms for research, development, and “micro scale up” continue to be needed.

Another interesting trend which may offer a way to reduce resource use is multiplexing. Multiplexing is an analytical approach that allows the simultaneous detection and quantification of large number of biomolecules in small volumes of samples. Benefits of multiplexing, depending on the specific technique used, include high sensitivity and accuracy, low cost per analysis, and short time of analysis. Examples of specific applications include

in immunoassays, deoxyribonucleic acid (DNA) sequence analysis, detection of toxins, allergens, pathogens, antibiotics, and among others.

For experimentation using standard approaches, the waste management hierarchy in Figure 5 can be used to decrease environmental impacts. In the first instance, employment of management strategies to minimize requirements for chemicals and hazardous materials either by avoiding use completely or reducing use is recommended. Recycling, recovering, and treatment options may be considered only if necessary followed by disposal of chemicals and hazardous materials in appropriate landfills only as the last recourse. Other approaches to be considered include the use of energy-efficient and environmentally friendly appliances and construction materials, reduced energy use for lighting, water conservation approaches, and improving building designs.

Furthermore, the use of adequate experimental designs can significantly reduce the number of tests to successfully develop a new product. *In silico* experimental approaches can provide insights into the viability of hypotheses without the need for experimentation which would minimize environmental impact. Additionally, developments in social media offer completely new communication and collaboration platform which opens up new models for doing business and R&D. Harnessing of ideas from the open market rather than investing millions of dollars to reinvent the proverbial R&D wheel is now considered an economically viable business model. The terms “open innovation” and “mass innovation” are increasingly being used in R&D and industry. Mass innovation refers to when a wide range of people and their different but complementary insights are brought together, to generate novel ideas by thinking outside the box [43]. Massidea.org provides an example of such a concept which is founded on series of innovation theories and is a free of charge open innovation community where people can share their ideas, discuss today’s challenges as well as visions of the future, which are key factors when creating new innovations [43]. The idea to innovation continuum is very vast and requires significant financial, human, capital, energy, and time investments.

Beyond construction, chemical management, and waste minimization, greening of R&D should include efforts toward enhanced industrial collaboration, partnerships, inter-laboratory collaboration, and use of the services of specialized analytical laboratory services when appropriate [6]. To be successful in such collaborative efforts, integrity, interdependence as well as approaches for managing intellectual property (i.e., copyright, confidential information, patents, trade secrets, trademarks, designs, and plant breeder’s rights) are required to ensure openness, smooth knowledge translation, and effective technology transfer.

## Social Perspectives Regarding Green Technologies

The definition of green technology or green agriculture is very fluid and often depends on the user and the context. The ultimate user of novel technologies, products, and in this instance, food is the consumer. Social perspectives of novel alternative technologies and approaches should therefore be taken into consideration in both process and product development. Consumers are confronted with an incredible amount of choice each day and their decisions are based on perceptions which may or may not be evidence-based. Choices made by consumers, nevertheless, have significant impacts on producers and processors and ultimately the economy.

Public understanding of food production and processing technologies, and their benefits and limitations will either be congruent with, or opposed to, that of scientific experts [27]. Consumers have not always lauded the intentions of the food industry due to disparities in the approaches used by the private sector. Social pressures on companies in relation to environmental issues have required that companies conform in order to avoid the consequences of non-conformity (e.g., legal penalties, public protests, and loss of market share to competitors), whereas some have responded by making fundamental changes in their practices and technologies, others avoid change through the use of public relations offensives or other avoidance tactics [27] and references therein. This partly explains the cynicism between consumers and the private sector in regard to “green claims.”

Consumers are interested in the environmental impacts of agricultural and food production practices but they also require that product quality, safety, nutrition, and price not be compromised. Research shows that the acceptability of food technologies lies along a perceived risk and benefit continuum [31]. Improving benefits such as nutritional value, taste, and shelf life enhances a product’s acceptability [15], whereas perceived risks (e.g., presence of toxic by-products) negatively correlates with intention to purchase, intention to use, and overall acceptability [13, 31, 47]. In general, although environmental impact of food production and processing is not the first benefit sought after by consumers in regard to food technologies, it is among their expectations [27].

The publication of Rachel Carson’s *Silent Spring* revealed the dangers of chemicals used in agriculture for ecosystems and the risk they present to human health [28]. Considering the awakening provoked by what can be called the side effect of the Green Revolution, it is not surprising that the “Gene Revolution” has also aroused some suspicion. This has contributed to the growing number of consumers who turn to some sort of alternative models of food consumption such as organic agriculture, buying local,

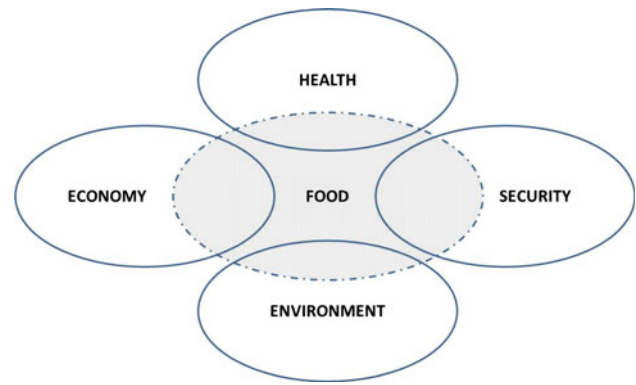
dealing directly with the producer, fair-trade, and eco-labelling (e.g., environmental and sustainable agriculture certification and evidence of social responsibility) [28].

Another major social challenge is the current trend toward using “food” for biofuels and bio-based products. At least 100 times the total global crop net primary production will be needed to meet current petroleum needs. Schenk [45] argues that there is simply not enough land to meet global fuel needs with biofuels and that we are very near the breaking point as a collective, with the real risk of not having enough food to feed everyone. A similar argument applies to bio-based plastics. Agriculture is the overwhelming source of nitrous oxide (a more potent greenhouse gas than CO<sub>2</sub> as previously mentioned) emissions in the United States (United States, EPA [54]. Climate friendly farming which focuses on agricultural practices which reduce greenhouse gas emissions (e.g., no till farming, mixed agriculture as opposed to monoculture) will be increasingly needed.

### Current and Future Challenges

Continued use of current agricultural practices and technologies will not be sustainable in the long term. New business models based on finding the right balance between environment protection and economic profits are required. As shown in Fig. 6, there is a close interrelationship between food, health, economy, security and the environment. The profitability in environmental sustainability needs to become more palpable for the agriculture and agri-food sectors. To go even further, the use of agriculture not only to reduce emissions but to act as sink for other sectors through carbon sequestration must be considered. There is growing need for new technologies (e.g., through novel engineering, equipment, processing, and packaging designs) to address these emerging challenges. This is particularly of interest as various technologies will be needed to address challenges along the entire value chain. Furthermore, efforts will need to be targeted to address site-specific challenges (i.e., farm, regional, national, and international needs).

Perhaps, even more challenging will be the need for (a) technologies to accurately predict and counter expected increases in global temperatures and sea levels and attendant impacts on agriculture and capacity for processing; (b) sustainable methods to increase food yields; and (c) technologies to prevent food spoilage (especially in developing countries) where the climate is a threat to shelf life and where there is a lack of a cold chain to preserve foods. Successful diffusion and adoption of these sustainable technologies will hinge on their economic viability. Currently, there appears to be a lack of markets for



**Fig. 6** Schematic of the interrelationship between food, health, economy, security, and the environment

environmental attributes (e.g., eco-labels with economic viability) which may need to be addressed through policy interventions (e.g., incentivization, rewards for uptake, and regulations).

Another major challenge is the ongoing loss of biodiversity and its potential impacts on health and the environment. Biodiversity is being lost at an unprecedented rate as a result of current agricultural and industrial practices. Ultimately, food production and processing must be done with the objective of providing sustainable diets to all. The FAO [24] defines “sustainable diets as those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Such diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe and healthy, while optimizing natural and human resources.” Improving food systems for sustainable diets requires an interdisciplinary effort to address the problems of malnutrition, the degradation of ecosystems, and the erosion of biodiversity caused, at least in part, by modern day food systems and dietary patterns [12]. A concerted effort will thus be required to increase the diversity of foods produced in different regions of the world and to incentivize food processors to expand their use of diverse whole foods and food ingredients in food formulation and processing.

Intensive research is needed to address these challenges. As reducing cost to consumers will be important, this raises the all-important question of who must bear the cost of R&D. As indicated by the OECD, “green growth policies which place a premium on environmental protection may constrain agricultural and fisheries output, reduce global food supply and entail adjustments in the use of human, financial and natural resources in the short-term, but implications in the longer-term should be mutually reinforcing in terms of environmental sustainability, economic growth and social well-being” [41].

## Conclusion

The relationship between food, physical and environmental health, and the economy has become increasingly evident. Finding a balance between food supply and demand in a manner that is sustainable and which ensures the long-term survival of humankind will be one of the most important challenges facing the agriculture and agri-food sectors over the next 40 years. “Increasing productivity in a sustainable manner will require according high priority to research, development, innovation, education and information in the agriculture and agri-food sectors” [41]. A variety of approaches as outlined above can be considered to reduce the impact of agricultural practices while ensuring adequate supplies of food to feed the ever growing world population. To ensure success, regional, national, and international collaborative efforts along the food chain continuum will be increasingly required. Additionally, sustainable food engineering approaches which harness the power of open innovation and which take into consideration social, environmental, economic concerns will be needed.

**Conflict of interest** There are no conflicts of interest to report. The authors are employees of Agriculture and Agri-Food Canada. The opinions expressed are the Authors’ own.

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## References

- Akhtar H (2012) Reducing process-induced toxins in foods. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
- Altieri MA (1999) The ecological role of biodiversity in agroecosystems. *Agric Ecosyst Environ* 74:19–31
- Arcand Y, Maxime D, Zareifard R (2012) LCA of processed food. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
- Bloom J (2010) American wasteland: how America throws away nearly half of its food (and what we can do about it). Da Capo Press, Boston, MA
- Bouwman AF, Boumans LJM, Batjes NH (2002) Modeling global annual N<sub>2</sub>O and NO emissions from fertilized fields. *Global Biogeochem Cycles* 16(4):1080
- Boye JI, Maltais A, Bittner S, Arcand Y (2012) Greening of research and development. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
- Boye JI, Arcand Y (2012) Green technologies in food production and processing. Springer, New York
- Brentrup F, Küsters J, Lammel J, Kuhlmann H (2000) Methods to estimate on-field nitrogen emissions from crop production as input to LCA studies in the agricultural sector. *Int J Life Cycle Assess* 5:349–357
- Brentrup F, Küsters J, Lammel J, Kuhlmann H (2002) Life cycle impact assessment of land use based on the Hemeroby concept. *Int J Life Cycle Assess* 7:339–348
- Brentrup F (2012) LCA of crop production. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
- Bruntland Commission (1987) Our common future: report of the world commission on environment and development, published as annex to general assembly document A/42/427, development and international cooperation. Oxford University Press, New York
- Burlingame B, Charrondiere UR, Dermeni S, Stadlmayr B, Mondovi S (2012) Food biodiversity and sustainable diets: implications of applications for food production and processing. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
- Cardello AV, Schutz HG, Leshner LL (2007) Consumer perceptions of foods processed by innovative and emerging technologies. A conjoint analytic study. *Innov Food Sci Emerg Technol* 8(1):73–83
- Conant RT, Paustian K (2002) Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochem Cycles* 16(4):1143–1152
- Delgado-Gutierrez C, Bruhn CM (2008) Health professionals’ attitudes and educational needs regarding new food processing technologies. *J Food Sci Educ* 7(4):78–83
- Dyer JA (1989) A canadian approach to drought monitoring for famine relief in Africa. *Water Int* 14(4):198–205
- European Commission—Joint Research Centre—Institute for Environment and Sustainability (2010) International reference life cycle data system (ILCD) handbook—general guide for life cycle assessment—detailed guidance. First edition March 2010. EUR 24708 EN. Publications Office of the European Union; Luxembourg
- Fearnside PM (1980) The effect of cattle pasture on soil fertility in the Brazilian Amazon: consequence for beef production fertility. *Trop Ecol* 21(1):125–137
- Fearnside PM (1990) Deforestation in Brazilian Amazonia. In: Woodwell GM (ed) The earth in transition: patterns and processes of biotic impoverishment. Cambridge University Press, New York
- Food and Agriculture Organization of the United Nations (FAO) (2003) World agriculture: towards 2015/2030, an FAO perspective. Earthscan Publications Ltd, London
- Food and Agriculture Organization of the United Nations (FAO) (2006) World agriculture: towards 2030/2050, an FAO perspective. Interim report
- Food and Agriculture Organization of the United Nations (FAO) (2009a) The state of food in agriculture: livestock in the balance. Electronic Publishing Policy and Support Branch-Communication Division, FAO, Rome
- Food and Agriculture Organization of the United Nations (FAO) (2010) FAOSTAT statistical database. Rome. Accessed Mar 2010
- FAO (2010) International scientific symposium ‘biodiversity and sustainable diets’, final document. Available at <http://www.fao.org/ag/humannutrition/25915-0e8d8dc364ee46865d5841c48976e9980.pdf>
- Ferguson A (2012) Population matters for a sustainable future. *OPT J* 12(2):4–6
- Gagnon N (2012) Introduction to the global agri-food system. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
- Gauthier EG (2012) Green food processing technologies: factors affecting consumers’ acceptance. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York



28. Gendron C, Audet R (2012) Key drivers of the food chain. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
29. Grabowski S, Boye JI (2012) Green technologies in food dehydration. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
30. Grabowski S, Marcotte M (2003) Pretreatment efficiency in osmotic dehydration of cranberries. In: Chanes JW, Velez-Ruiz JF, Barbosa-Canovas GV (eds) Transport phenomena in food processing. CRC Press, Boca Raton
31. Henson S, Annou M, Cranfield J, Ryks J (2008) Understanding consumer attitudes toward food technologies in Canada. *Risk Anal* 28(6):1601–1617
32. Hermansen JE, Nguyen TLT (2012) LCA and the agri-food chain. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
33. Hoekstra AY, Chapagain AK (2007) Water footprints of nations: water use by people as a function of their consumption pattern. *Water Resour Manag* 21:35–48
34. Hunt R, Franklin W (1996) LCA—how it came about. *Int J Life Cycle Assess* 1(1):4–7
35. LeJeune JT (2003) E. coli O157 in dairy cattle: questions and answers. Ohio State University Extension Fact Sheet. VME-16-03. Food Animal Health Research Program, Wooster, Ohio. <http://ohioline.osu.edu/vme-fact/0016.html>. Accessed 15 Jun 2010
36. Mena C, Stevens G (2010) Delivering performance in food supply chains: an introduction. In: Mena C, Stevens G (eds) Delivering performance in food supply chains, 1st edn. Woodhead Publishing, London
37. Menzi H, Oenema O, Burton C, Shipin O, Gerber P, Robinson T, Franceschini G (2010) Impacts of intensive livestock production and manure management on ecosystems, chapter 9. In: Steinfeld H, Mooney AH, Schneider F, Neuville EL (eds) Livestock in a changing landscape, vol. 1: Drivers, consequences and responses. Island Press, Washington, DC, pp 139–163
38. Nazzaro F, Fratianni F, Coppola R (2012) Nano and micro analyses. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
39. Nellemann C, MacDevette M, Manders T, Eickhout B, Svihus B, Prins AG, Kaltenborn, BP (2009) The environmental food crisis—the environment's role in averting future food crises: a UNEP rapid response assessment. United Nations Environment Programme (UNEP)/GRID-Arendal, Birkeland Trykkeri AS, Norway
40. Ngadi MO, Latheef MB, Kassama L (2012) Emerging technologies for microbial control in food processing. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
41. OECD (2011) A green growth strategy for food and agriculture: Preliminary report. OECD 2011. [www.oecd.org](http://www.oecd.org)
42. Pirog R, Van Pelt T, Ensayan K, Cook E (2001) Food, fuel and freeways: An Iowa perspective on how far food travels, fuel usage, and greenhouse gas emissions. Leopold Center for Sustainable Agriculture, Ames
43. Santonen T (2012) Massidea.org—a greener way to innovate. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
44. Schader C, Stolze M, Gattinger A (2012) Comparison of traditional vs alternative (organic) farming. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
45. Schenk R (2012) The fallacy of biobased materials. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
46. Selke SEM (2012) Green packaging. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
47. Siegrist M, Cousin ME, Kastenholz H, Wiek A (2007) Public acceptance of nanotechnology foods and food packaging. The influence of affect and trust. *Appetite* 49:459–466
48. Simpson BK, Rui X, XiuJie J (2012) Enzyme-assisted food processing. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
49. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
50. Seinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) Livestock's long shadow: environmental issues and options. FAO, Rome
51. Stevens GC (1989) Integrating the supply chain. *Intern J Phys Distrib Mater Manag* 19(8):3–8
52. Stolze M, Pierr A, Häring AM, Dabbert S (2000) Environmental impacts of organic farming in Europe. Organic farming in Europe: economics and policy, vol. 6. Universität Stuttgart-Hohenheim, Stuttgart-Hohenheim
53. UNECE/EMEP (2007) EMEP/CORINAIR emission inventory guidebook—2007. Technical report No 16/2007. EEA (European Environment Agency), Copenhagen, Denmark
54. United States. Environmental Protection Agency (2011) Draft inventory of the U.S. greenhouse gas emissions and sink: 1990–2009. [http://www.epa.gov/climatechange/emissions/downloads/11/US-GHG-Inventory-2011-Complete\\_Report.pdf](http://www.epa.gov/climatechange/emissions/downloads/11/US-GHG-Inventory-2011-Complete_Report.pdf)
55. Vayssières J, Rufino MC (2012) Management of agricultural inputs, waste and farm outputs: present and future best management practices. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
56. Vergé XPC, Worth DE, Desjardins RL, McConkey BG, Dyer JA (2012) LCA of animal production. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
57. Wakeland W, Cholette S, Venkat K (2012) Transportation issues and reducing the carbon footprint. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York
58. Weber CL, Matthews HS (2008) Food-miles and the relative climate impacts of food choices in the United States. *Environ Sci Technol* 42(10):3508–3513
59. World Health Organization (WHO)/Food and Agriculture Organization of the United Nations (FAO) (2003) Diet, nutrition and the prevention of chronic diseases. WHO/FAO Expert Consultation, Geneva, Switzerland. (WHO Technical Report Series;916)
60. Zervas G (1998) Quantifying and optimizing grazing regimes in Greek mountain systems. *J Appl Ecol* 35:983–986