9 Sustainability and Environmental Issues in Food Processing

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9.1 Introduction

The United Nations has defined sustainable development as development that meets "the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Therefore, a sustainable food chain implies that the entire food chain must be both competitive and resilient if it is to ensure a secure, environmentally sustainable, and healthy supply of food. There are currently a number of challenges to be overcome if we are to develop a truly sustainable food chain. Agricultural production has been estimated to contribute between 17% and 32% of global greenhouse gas emissions; approximately 30–50% of produced food is wasted (Boye & Arcand, 2012), yet widespread malnutrition continues to occur, while food processing accounts for 25% of water consumption worldwide (Baldwin, 2009). An assessment of sustainability should consider environmental, economic, and societal impacts.

When taken holistically, the food chain comprises a number of steps: food production, processing (including transport and distribution), retail, consumption, and end of life (Baldwin, 2009). While it is important to note the environmental impact of food production (i.e. land use change, climate change), the primary focus of this chapter will be food processing (i.e. waste generation, energy use). This chapter will first present motivating factors that are driving the sustainable food processing agenda. A discussion of the key environmental impacts associated with food processing will follow. To achieve better sustainability in food processing, a number of emerging and established technologies and tools will need to be employed; therefore the application of green technologies and sustainability assessment methods in food processing will finally be presented.

9.2 Sustainable food processing drivers

The key drivers in the move towards sustainable food processing are legislative, economic, consumer or corporate based.

9.2.1 Legislative drivers

According to Cooke (Cooke, 2008), environmental legislation relevant to the food processing industry can be considered at three levels:
- at a point in the environment
- at the point of emission
- at the process that creates the emission.

In general, there has been a move towards the third level, that is, controlling the process that emits the pollutant, rather than emissions deemed detrimental to the environment. In Europe, such control effort emerged as the Integrated Pollution Prevention and Control Directive (European Commission, 2008), which has now been superseded by the Industrial Emissions Directive (European Commission, 2010). The objective of such legislation is to minimize pollution from various industrial

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sources throughout the European Union, including the food and beverage sector. This is achieved through the provision of a "license to operate" to premises that meet certain conditions. Permits must take into account the whole environmental performance of the plant, including aquatic, air and solid waste generation, use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure (European Commission, 2010). Also notable is that emission limit values in the permit must be based on the use of the "best available techniques" (EU Joint Research Centre, 2013); environmental inspections of the facility must be carried out and the public has the right to participate in the decision-making process. Hence, it can be ensured that food processing facilities, through design or upgrade, meet international environmental standards. Therefore, new facilities must be designed at the earliest stage to meet these environment requirements, while older plants may need to be retrofitted with updated technologies.

In the EU, member states are legally bound to optimize the treatment of biowaste. The "waste hierarchy" states that the prevention of waste is the best option, followed by reuse, recycling, and energy recovery. Disposal method, such as landfilling, is defined as the worst environmental option. This has resulted in legislation requiring member states to reduce the amount of biowaste they send to landfill (European Commission, 1999). Therefore, options for waste disposal by food processors are limited, particularly in countries such as Ireland, which were previously heavily reliant on landfill. This has played a role in the rising interest in alternative use and disposal options for waste streams in the food processing sector. This will be further discussed in section 9.3.2.

It should also be noted that there is a move towards linking legislative drivers with economic drivers to improve overall sustainability. For example, the EU Emission Trading System (ETS) is mandatory for food and beverage companies operating combustion installations above a capacity of 20 MW. Examples of facilities which have fallen under phase III of the ETS include those involved in snack food production, distilling and brewing, butter and cheese production, and coffee processing (UK Department of Energy and Climate Change, 2012). The ETS is a "cap and trade" scheme, which has goals of establishing an allowance-trading scheme for emissions, and promoting reductions of greenhouse gases, in particular carbon dioxide. Each EU country is required to submit National Implementation Measures (NIMs) for approval by the European Commission. NIMs determine the levels of free allocation of allowances for installations during the current phase of ETS. These allocations are based on EU community-wide harmonized rules (European Commission, 2011). Through the growth of a carbon market, companies can buy allowances to meet their compliance requirements or sell their surplus allowances. Companies buy allocations through auctions. Two auction platforms are already in place. The European Energy Exchange (EEX) in Leipzig is the common platform for the large majority of countries participating in the EU ETS. The EEX also acts as Germany's auction platform. The second auction platform is ICE Futures Europe (ICE) in London, which acts as the United Kingdom's platform (European Commission, 2013).

9.2.2 Economic drivers

Economic drivers of sustainable food processing can take a number of forms. It has been projected that world marketed energy consumption will grow by 53% between 2008 and 2035 (EIA, 2011). This, coupled with an expectation that energy prices will continue to increase in the long term (EIA, 2011), has become a driver for companies, including food processors, to reduce energy consumption. Selected unit operations in food processing facilities are particularly energy intensive, for example, drying and evaporation. It has been suggested that energy can account for up to 10% of the total production costs for products requiring these unit operations (Marechal & Muller, 2008). While this figure is low in comparison with other industries (oil refining ~60% of total production cost), rising energy costs have forced energy saving and energy management programs to the forefront of many food processing businesses.

Between 30% and 50% of incoming raw materials can end up as waste material during food processing (Henningsson et al., 2004; Schaub & Leonard, 1996). In the UK, food manufacturing generates approximately 2.5 billion kg of food waste annually (Hall & Howe, 2012); in the US, the EPA estimates that it costs approximately $1 billion to dispose of food waste (Kosseva & Steve, 2009). In the EU, landfilling of biowaste is a major concern, with approximately 40% of it ending up in landfill. As mentioned in section 9.2.1, there is a legislative requirement for EU member states to reduce the use of landfill as a waste disposal option. To encourage this, governments have increased the levy on landfill to provide an economic incentive for companies to move to more sustainable methods of waste disposal. Historically, some food waste streams would have been used as animal feed supplements, e.g. whey as pig feed. However, with the recognition of the added value of whey components, the trend is now to utilize it in a much more sustainable manner (see section 9.3.2). Therefore, as a result of the pressure to reduce waste and utilize it more sustainably, there has been an increased focus on using food processing biowaste streams to develop waste-to-energy systems and value-added products, as well as on finding new, more sustainable, waste disposal options. These developments are discussed in more detail in section 9.3.2.

9.2.3 Consumer drivers

In a market economy consumer power and demand can drive market developments and therefore consumer choice and preference could be a driver of sustainability in the food processing industry. A number of studies have found that consumers will differentiate products on the basis of sustainability (Jaffry et al., 2004; Kearney, 2010). However, consumer choice is complex and will be influenced by a multitude of factors including cost, convenience, and habit (Vermeir & Verbeke, 2006). It is estimated that approximately 10% of the population are "socially conscious purchasers" (Sahota et al., 2009). Product claims can range from the use of recyclable material and product life cycle sustainability, to overall company sustainability commitments. The role of certified products, i.e. products verified by a third party to meet a set of standards, in promoting sustainable food processing through consumer-driven demand is growing. Certification can have a regulatory role, such as certification required by the EU or US Food and Drug Administration (FDA), or can occur through voluntary schemes, e.g. Fairtrade or Rainforest Alliance. Schemes such as Fairtrade and Rainforest Alliance focus on the provision of sustainable livelihoods and/or protecting ecosystems and biodiversity in places where products or raw materials originate, while other schemes, e.g. Mobius Loop, indicate that a product or part thereof can be recycled where facilities are available. For voluntary certification schemes to provide maximum benefit to food processors, claims need to be credible, easily understood, and trusted by consumers.

A number of studies have investigated consumer purchasing choices of "green labeled" products. Jaffry et al. (2004) investigated consumer choices for quality and sustainability-labeled seafood products in the UK. They carried out 600 in-home interviews and found that certification denoting sustainability or quality had a significantly positive influence on product choice, with sustainability appearing to have the greatest positive influence on the probability of choice. However, they also found negative attitudes held towards non-governmental certifiers, over governmental certifiers, highlighting the importance of consumer trust in certification schemes. While such studies indicate the potential value to food processors of adopting green labels, it is also critical to ensure that consumers recognize, understand, and value on-package information on production standards (Hoogland et al., 2007).

Research has shown that when food products (chicken, milk, salmon) are labeled with either (a) a certified organic logo combined with details about the animal welfare standards (e.g. outdoor access, painless stunning/killing, organic fodder, etc.), (b) just the certified organic logo, or (c) a statement in which the product was attributed to the world market (e.g. conforms to legal production standards), many consumers failed to realize that the organic logo presented alone (option b) covered all three categories (Hoogland et al., 2007). In fact, they were inclined to underestimate the distinctive advantage of the logo and were more positive towards products that presented both the logo and details of animal welfare.

9.2.4 Corporate performance

Food processing companies are, in general, attempting to address environmental issues. Many companies are now including sustainability as a corporate performance measure (Pirog et al., 2009). There are three "dimensions" of sustainability:

- environmental sustainability, incorporating the management of the effects of human activity so that they do not permanently harm the natural environment
- economic sustainability, which involves managing the financial transactions associated with human activities so that they can be sustained over the long term without incurring unacceptable human hardship
- social/cultural sustainability, i.e. allowing human activity to proceed in such a way that social relationships between people and the many different cultures around the world are not adversely affected or irreversibly degraded.

In order for a business to be truly sustainable, it must succeed in all three categories. This has become known as the "triple bottom line."

Environmental sustainable corporate performance (SCP) is defined as "Good housekeeping through prevention of pollution and waste and efficient use of scarce resources" (Gerbens-Leenes et al., 2003). The challenge for companies can often be how to accurately measure their performance in each of these three criteria. Often companies focus on local-level environmental impacts associated with their operation using a large number of indicators (Gerbens-Leenes et al., 2003). Hence, assessment of sustainability under all three pillars at not only a local but a regional and global scale may be omitted. Overall, the rise in demand for high-quality food, coupled with the fact that the environmentally conscious consumer of the future will consider ecological and ethical criteria in selecting food products, will, in conjunction with legislative, economic, and corporate drivers, play a role in the development of truly sustainable food processing (Roy et al., 2009).

9.3 Environmental impact of food processing

The role of food processing is to convert raw materials (fruit, vegetables, milk, cereals, etc.) into food products fit for human consumption. In addition to raw materials, the major inputs into the system are water and energy. Therefore, the main environmental impacts of the food processing sector are aquatic, atmospheric and solid waste generation, which are influenced by the quantity of resources utilized, waste produced, and transport used in the processing system. Successful management of water and energy resources in food processing is key to cost-effective sustainability practices. Environmental sustainability can be achieved by developing and implementing alternative environmental best-practice technologies and products that maximize the efficient use of resources and achieve cost savings, while minimizing negative human and environmental impacts (Clark, 2010).

9.3.1 Energy

The food industry is a major source of atmospheric emissions, mainly caused by extensive energy use. The food industry consumes a large quantity of energy for heating buildings, in processing and providing processed water, and for refrigeration and the transportation of raw materials and products (Pap et al., 2004). Such energy use contributes to greenhouse gas (GHG) emissions, especially carbon dioxide emissions (Roy et al., 2009). Although GHG emissions are a particular challenge for the food production sector, which relies heavily on transport and fertilizer use, energy reduction and management in food processing have also become increasingly important, as discussed in section 9.2.2, as a result of economic and legislative pressure. Over recent years, the food industry has made progress in reducing its energy consumption through process optimization and control, energy recovery and recycling systems, and good manufacturing practices. This trend is likely to continue due to the enforcement of legislation in carbon trading systems, e.g. EU ETS (Sellahewa & Martindale, 2010).

Development of energy-efficient equipment designs is, today, standard in the food processing industry. Regeneration is employed in processes such as milk pasteurization to accomplish considerable energy savings. Raw milk entering a plate heat exchange is preheated to ~55 °C by hot pasteurized milk on the other side of the plates; the raw milk then moves from the regeneration section to the next section of the plate heat exchanger, where hot water is used to heat the milk to the required processing temperature of 72 °C. The use of regeneration reduces the amount of hot water required to heat the milk to the pasteurization temperature, thereby reducing the steam/energy requirement of the process. By utilizing regeneration, pasteurization is 95% efficient at recovering heat. Multieffect designs are also standard for processes such as evaporation. Multiple-effect evaporation is evaporation in multiple stages, whereby the vapors generated in one stage serve as a heating source to the next stage. In a multieffect evaporator, for each kg of water evaporated, the quantity of steam consumed is inversely proportional to the number of effects and the quantity of cooling water utilized in the condenser is inversely proportional to the number of effects (Berk, 2009).

Processes such as pasteurization are clearly highly efficient in term of heat recovery. However, in the UK it is still estimated that approximately 2.9 TWh of recoverable heat is wasted annually by the food and beverage processing sector (Law et al., 2013). The successful capture and utilization of such waste heat have the potential to play a critical role in improving the overall energy efficiency of this sector. It is estimated that the recovery of this waste heat could potentially result in cost savings of £70 m and emissions savings of 514,080 tCO_2eq for the UK food and beverage processing industry annually (Law et al., 2013). Meeting such targets will require a number of challenges to be overcome. It is often difficult to exactly match the waste heat with suitable heat sinks, thereby reducing the percent of heat recovered. It is also very difficult to recover waste heat in the range of ambient to 60 °C. Besides the pasteurization and evaporation processes mentioned above, other sources of waste heat include ovens, kilns, dryers, refrigerators, boilers, power plants, and air compressors. Uses for waste heat can be categorized as follows.

- Use within its originating process (e.g. regeneration).
- Use within another process.
- Use of cooling via absorption refrigeration cycle.
- Use for space and water heating (Reay, 2008).

Regardless of its end use, the waste heat source must meet food processing hygiene requirements for the process in which it will be used. Examples of the use of waste heat in other process include:

- recovery of waste heat from two 50 kW compressors, which is used to preheat boiler feed water, resulting in a 3% reduction in boiler energy demand at a biscuit factory (Reay, 2008)
- recovery of waste heat from the fryer section and exhaust stream of a potato crisps manufacturing plant is used to drive an organic Rankine cycle system for power generation and could have the potential to meet the average power requirement as well as 98.58% of the peak power requirement of the manufacturing process (Aneke et al., 2012).

Conventional refrigeration has a high electricity demand. However, the use of waste heat to drive alternative refrigeration cycles can reduce this. In the absorption refrigeration cycle, waste heat can be used to drive a generator where ammonia is evaporated off. The resulting vapor contains some water, so a rectifier and dephlegmator are included to reduce this. This vapor flow condenses into liquid in the condenser, rejecting the heat of condensation. Condensed liquid passes through a valve and low-pressure liquid enters an evaporator to evaporate the heat required for evaporation. The resulting vapor then enters the absorption cycle and is ultimately returned to the generator. While this cycle has the benefit of using waste heat, its coefficient of performance is lower than a conventional mechanical vapor compression cycle. Therefore the absorption cycle can be combined with other refrigeration cycles, such as the ejector refrigeration cycle, to improve the overall coefficient of performance.

In order to improve the sustainability of the food industry significantly, technological advancements in energy efficiency will need to be coupled with increased use of renewable energy such as solar, wind, and bioenergy. Companies, for example Dole (2008) and Kettle Foods (2009), have started to incorporate renewable energy sources, such as biodiesel, wind, and solar energy, to improve their sustainability. Such choices need to be combined with increased efficiency, as highlighted by a recent study of the Australian prune-drying industry, which demonstrated that up to 60% of energy could be saved by optimization and control of the process and utilizing solar energy (Sellahewa & Martindale, 2010). It is also possible to convert food waste stream to energy to reduce energy requirements and cost; this will be discussed in section 9.3.2.

9.3.2 Solid waste

The food industry is a major generator of both solid waste (food, packaging, etc.) and liquid effluents (see section 9.3.3) throughout the process chain. Traditionally, food wastes go to landfill, but this is not now deemed appropriate as it poses a serious environmental concern (see section 9.2.2). When food is wasted, it also contributes to GHG emissions and water usage, as energy and water are used in growing the raw materials, processing the product and in storage and distribution. In a recent life cycle assessment carried out with fresh Australian mangos, it was shown that waste contributed to 53% of the overall GHG emissions during production, distribution, and consumption phases (Ridoutt et al., 2010a). Therefore food waste must be tackled on multiple levels, i.e. processor, distributor/retailer, and consumer.

The major contributors to solid waste from food processing are fruit processing, cocoa/chocolate/confectionery, brewing/distilling, and meat processing (My Dieu, 2009). For example, poultry processing produces 35 kg of biowaste per 1000 birds processed, while distilleries produce 300 kg of biowaste per tonne of final product (My Dieu, 2009). Clearly the composition of the biowaste stream is dependent on the process that generates it, and its composition will, in turn, determine how the waste must be processed. An effective waste management system will aim to reduce the volume of waste produced and recover value components within the waste, followed by treatment and discharge. The minimization of waste production can be achieved through good manufacturing practices, adequate process control, and appropriate equipment maintenance and design. If any of these criteria fail, there can be a decrease in process efficiency and an increase in product losses during production.

Approaches that extend shelf life are also important in reducing overall food waste. Processes such as food irradiation can extend shelf life of products such as potatoes (inhibits sprouting) and strawberries (inhibits growth of spoilage microorganisms). However, irradiation has not received widespread usage. Consumer acceptance of food irradiation varies from country to country, which has also hindered its adoption. It should also be noted that significant efforts have been made by many food processors to reduce food packaging. For example, in the UK, a number of retailers and processors have signed up to the

Waste and Resources Action Program (WRAP) and the Courtauld Commitment 2 (www.wrap.org.uk), whereby they aim, among other things, to reduce packaging by 10%.

For a long time, waste streams were just viewed as by-products of food processing, but today they are often considered as valuable additional revenue streams. Therefore, waste streams are often further processed in order to remove all valuable components prior to discharge. These components are upgraded into value-added products. A good example of this is whey from cheese making. Historically, whey was fed to animals but modern cheese making now encompasses whey processing and extraction of value-added products. In general, fat is separated from the waste stream and can be used for butter manufacture; the reduced fat whey is then subjected to reverse osmosis and membrane filtration to separate out the lactose and whey protein. The resulting water can then be reused within the cheese-making facility. Another example of waste upgrading is presented by Laufenberg et al. (2003), who examined the upgrading of vegetable residues for the production of novel types of products. Plessas et al. (2008) investigated the upgrading of waste orange pulp. They used the pulp for cell growth of kefir and found that bread produced by immobilized kefir on orange pulp had an improved aromatic profile in comparison with bread produced by baker's yeast, and preliminary sensory evaluation of the produced bread was acceptable (Plessas et al., 2008).

Food waste streams can also be used as substrates to generate energy, thus improving sustainability (Sellahewa & Martindale, 2010). These waste-to-energy systems have received much attention in recent years (Banks et al., 2011; Caton et al., 2010; Curry & Pillay, 2012; El-Mashad & Zhang, 2010; Hall & Howe, 2012; Ike et al., 2010; Lai et al., 2009). Options for the conversion of waste to energy include anaerobic digestion (AD), direct combustion, and gasification. The selection of a waste-to-energy conversion process will be dependent on waste composition; in general, waste with a moisture content over 50% will be suitable for biological conversion such as AD, while lower moisture content waste will be more suited to thermochemical conversion (e.g. combustion). In AD, microorganisms under anaerobic conditions break down organic material and produce a biogas that is composed of mainly carbon dioxide and methane. Methane is a high-value fuel, producing 12,000 kcal kg^{-1} with a clean burn (My Dieu, 2009). The four stages of AD are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In hydrolysis, carbohydrates, lipids, and proteins are broken down into simple sugars, fatty acids, and amino acids, which are subsequently broken down into carbonic acids, volatile fatty acids, and alcohols during acidogenesis. The by-products are hydrogen, carbon dioxide, and ammonia. These products are converted into acetic acid during acetogenesis, with the release of carbon dioxide and water. In the final stage (methanogenesis), acetic acid and hydrogen are converted into methane (50–75%) and carbon dioxide (25–50%). This methane can then be upgraded to a suitable mainline standard.

In gasification, the organic material is exposed to high temperature under low oxygen conditions. This produces a syngas (carbon monoxide, carbon dioxide ,and hydrogen) which, like biogas, can be used as a fuel. Waste oil is another by-product of food processing that can be converted to energy. Kettle Foods, for example, converts 100% of its waste vegetable oil from its production process into biodiesel.

9.3.3 Water and waste water

Ensuring the sustainability of water systems is currently a major concern. The food industry is a large consumer of water across the food production chain, although according to Drastig et al. (2010), agricultural production has accounted for about 90% of global fresh-water consumption during the past century. It is also expected that water consumption for food production will need to increase to meet demands of a 50% larger global population. Milman and Short (2008) stated that 20% of the world's population currently lacks access to clean water and existing levels of access may deteriorate due to worsening urban water infrastructure, climate change, and environmental degradation.

Traditionally water was seen as cheap and plentiful in many parts of the world. This, along with legislation against the use of recycled water in processed foods (Sellahewa & Martindale, 2010), had reduced focus on water use reduction. However, this has recently changed. Increasing water costs and scarcity of supply, in addition to changes in legislation, have lead to increased efforts to improve water use efficiency in the food chain. These efforts will also have the impact of reducing the volume of waste water to be disposed of. Primarily, the focus of developments has been on maximizing water reuse and recycling (Kim & Smith, 2008). Water is key to food processing, as it is used for everything from washing raw material to equipment cleaning programs, as a heat transfer medium, and as a raw material itself. Equipment and process design can include the goal of reduced water requirements. In terms of water system design, three main design options can be considered, as defined by Kim and Smith (2008).

- **Water reuse**: water can be reused between operations. This depends on the water being of sufficient quality. Reused water can be mixed with fresh water if required.
- **Regeneration recycling**: the use of water reclaimed from waste-water treatment, and reused in the same operations.
- **Regeneration reuse**: the use of water reclaimed from waste-water treatment, and reused in a different operation to the one from which it was generated.

Waste-water treatment involves a number of steps. Preliminary treatment involves the removal of large suspended particles through screening and settling. This is followed by primary treatment wherein additional suspended material and material with a high biological oxygen demand (BOD) are removed through the use of coagulation, flocculation, clarification, and aeration. In the secondary treatment stage, systems such as activated sludge utilize microorganisms to reduce the biological and chemical oxygen demand (COD) of the waste along with a reduction in the particulate matter, nutrient, and odor of the waste. This water is non-drinkable but could be used to wash floors. Finally, in the tertiary treatment stage, operations such as membrane separation, pH correction, and ion exchange are used to produce water of potable quality. This reclaimed water could be used as process water but appropriate quality controls need to be in place, including a Hazard Analysis and Critical Control Point (HACCP) plan specifically dealing with the water recycling process. While this process could significantly reduce the volume of water food processing uses, it can be difficult for processors to adopt this approach. There is a significant capital investment required for the implementation of waste-water treatment to drinkable standards and while some companies may already be using technologies employed in tertiary waste-water treatment for other applications, for many there may be a significant technical challenge to be overcome. Finally, consumer acceptance of the use of recycled water as potable water is low and will require a change in consumer perception of the process (Casani et al., 2005). This may be achieved though linking ongoing campaigns aimed at increasing public awareness of the true value of water as well as the environmental impacts related to high consumption of water with the potential for reclaimed water to alleviate some of the pressure on our water resources without compromising public health or food quality.

Combining waste minimization efforts across the food processing chain with environmentally friendly preservation of the food product, the generation of waste can be minimized and the environmental sustainability of the process can be boosted (Pap et al., 2004). In addition, recovery and reuse of by-products are an option to further reduce the final quantity of waste requiring disposal.

9.4 Green technologies: examples in the food processing industry

Green technologies are defined as those that aim to satisfy consumer demands for high-quality products, while optimizing the production process in order to have the least impact on the environment. As discussed in section 9.3, optimization includes the reduced utilization of raw materials, energy, and water, while reducing the generation of process waste and effluent that may contain harmful organic solvents. Green technology also involves reducing the number of processing steps in industrial manufacturing to obtain the same products in fewer processing steps with less energy and waste materials. Life cycle assessment (LCA) is a method for evaluating the environmental impact of a product over its entire life cycle, from raw materials acquisition through processing, to the point of final consumption. Environmental impacts of green technologies are evaluated by LCA by considering land use, raw material consumption, atmospheric emissions, and water-borne pollutants. LCA is discussed in section 9.5.4. Green technologies can be considered as those that use less energy, utilize renewable energy sources and produce fewer waste products with more environmentally friendly disposal options. Processes that utilize “green chemistry,” defined by Manley et al. (2008) as the design, development, and implementation of chemical products and processes to reduce or eliminate the use and generation of substances hazardous to human health and the environment, have a role to play in improving the sustainability of food processing.

9.4.1 Separation and extraction technologies

Supercritical fluid extraction is a process whereby a gas or liquid, held at or above its critical temperature and critical pressure, is used as an extracting solvent. Carbon dioxide is commonly used in supercritical fluid extraction as it is inert, non-corrosive, non-flammable, odorless, and tasteless. The advantages of replacing conventional organic solvents with supercritical CO_2 are: a reduction in environmental impact; higher purity extracts can be achieved; reduction in the number of processing steps and the process time; and finally an absence of toxic solvent residues (Shi et al., 2012). Supercritical CO_2 fluid extraction has been used to extract caffeine from coffee (Tello et al., 2011). It was possible to extract 84% of the caffeine using 197 kg CO_2/kg coffee husks. The caffeine is not pure but can be washed in water to achieve 94% purity. Numerous studies have also used supercritical CO_2 fluid extraction to extract flavor compounds (Barton et al., 1992; de Haan et al., 1990; Doneanu & Anitescu, 1998; Khajeh et al., 2004; Oliveira et al., 2009; Yonei et al., 1995). Flavors included those from milk fat, spearmint, peach, and cherry.

Subcritical (also known as superheated) water extraction is another green separation technology. In this case, water under pressure and between 100 °C and 374 °C (critical point) is used as the extractant. The advantage of water is that when heated under pressure, its properties vary significantly. For example, as the temperature rises up to 200 °C, the polarity of the water decreases and its dielectric constant falls. In addition to having the same advantages as supercritical CO_2 extraction, subcritical water extraction has the advantage of the simplicity of using water as a solvent. It has been used to extract essential oils and bioactive compounds such as anthocyanins and total phenolics (Cheigh et al., 2012; Eikani et al., 2007; Hassas-Roudsari et al., 2009; He et al., 2012; Ko et al., 2011; Ozel et al., 2003; Singh & Saldana, 2011).

Mustafa and Turner (2011) also described a pressurized liquid extraction (PLE) process as a green technology, which uses water as a solvent. They described its application for extraction of bioactive compounds and nutraceuticals from plants and herbs whereby it can not only decrease solvent consumption but also improve the yield of the extracted product. PLE is a technique that involves extraction using liquid solvent at elevated temperature and pressure, which enhances the extraction performance compared to those techniques carried out at near room temperature and atmospheric pressure. Extraction performance is improved as PLE enables solvents to be used at temperatures above their atmospheric boiling point, therefore enhancing their solubility and mass transfer properties.

9.4.2 Non-thermal processing

Traditionally, microbial control was achieved in food processing by dehydration, thermal processing or refrigeration. However, novel and emerging technologies can be used for this application without some of the disadvantages of conventional methods, such as high energy requirements. These novel and emerging technologies are usually employed as part of a hurdle technology approach, i.e. in combination with each other or other control methods. Novel processing technologies such as ultrasound, high hydrostatic pressure (HHP), ohmic heating, and pulsed electric field (PEF) processing could all be considered as green technologies if they reduce the energy requirement of a process or replace chemicals used during processing. Ultrasound processing could be used to reduce the time required for processes such as freezing and drying, thereby reducing energy usage. Ohmic heating is a rapid heating technology that should reduce energy usage over conventional thermal processing. Jung et al. (2011) described HHP processing as a green technology in comparison with conventional thermal treatment due to its lower energy requirement and recycling of the pressurization fluid.

Technologies that optimize food processing to limit the unnecessary use of energy could also be considered green technologies. For example, the syneresis control technology described by Fagan et al. (2008) was developed with the goal of optimizing the length of the syneresis process to ensure a consistent high-quality final cheese product. However, it could also have the added benefit of reducing or eliminating the unnecessary heating and stirring of the cheese vats, thereby reducing energy consumption. Regardless of the green technology to be employed, it is vital that an LCA of the system is undertaken to ensure that the correct technology is selected for integration into the process.

9.5 Environmental sustainability assessment methods

This section outlines three different methodological approaches commonly used in estimating the environmental impacts associated with the production of food products based on life cycle thinking. The methods consist of carbon footprint (CF), ecological footprint (EF), and life cycle assessment (LCA). A basic explanation of carbon footprint and ecological footprint is given, along with a brief mention of methodological issues and applications. Life cycle assessment is discussed in more detail later in the chapter. A table with a clear breakdown of methodological issues associated with each of the assessment methods discussed here can be found in the article of Jungbluth et al. (2012).

9.5.1 Carbon footprint (CF)

The process of "carbon footprinting" has become increasingly popular over recent years, as climate change has become a major issue in the public conscience (Weidmann & Minx, 2008). Although there are many definitions of the term "carbon footprint," it is generally referred to as "the total amount of greenhouse gases emitted during a product's production, processing, retailing and consumption" (Plassmann & Edwards-Jones, 2009). CF accounting involves identifying and quantifying emissions data for the product over its entire life cycle. It is important that this is carried out in a methodologically consistent manner in order to ensure comparability of results from different studies. The UK carbon footprint standard was developed for the British Standards Institute in response to this requirement, which outlines specifications for assessing the life cycle GHG emissions of goods and services (jointly referred to as "products") (British Standards Institute, 2011). In addition to this, the International Organization for Standardization is currently developing a draft governing carbon footprinting. The standard, titled "ISO 14067 Carbon footprint of products. Requirements and guidelines for quantification and communication," has been released in a draft format (ISO, 2012). The strength of carbon footprinting is the overall simplicity and ease in calculation of results, easily expressed in a single carbon dioxide emissions value (Weidema et al., 2008). Additionally, these results can be readily identified with and placed in context for the public, thereby influencing consumer choices and decision making, as it is easy to compare between products (Samuel-Fitwi et al., 2012).

Despite the advantages of using carbon footprinting to calculate environmental product information, relying entirely on one indicator can be misleading, as it may result in oversimplification of results. Carbon dioxide emissions contribute to only one of several impact categories and cannot accurately reflect overall environmental system performance. For example, carbon dioxide emissions are mainly related to fuel-based energy use, and food production systems with no energy use are selected as environmentally preferred production systems; non-energy emissions potentially impacting the environment are completely ignored such as land use change and waste management (Samuel-Fitwi et al., 2012). This shows that a carbon footprint might be insufficient for full environmental information and thus the use of a multi-impact assessment tool such as the LCA is recommended for this purpose (Jungbluth et al., 2012).

Examples of food-related carbon footprints include dairy production (Casey & Holden, 2005; Rotz et al., 2010) and conventional food crop cultivation (Hillier et al., 2009; Röös et al., 2010).

9.5.2 Ecological footprint

The ecological footprint concept, first presented by Rees (1992), has evolved into the world's primary measurement of humanity's demands on nature (Wackernagel & Rees, 1996); this parameter is now widely used as an indicator for measuring environmental sustainability (Čuček et al., 2012). The ecological footprint can be defined as "a measure of how much area of biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices" (Global Footprint Network, 2012). The ecological footprint converts the human consumption of natural resources into a normalized measure of land area, referred to as global hectares (gha) (Samuel-Fitwi et al., 2012). Each gha represents the same fraction of the earth's total bioproductivity and is defined as "1 ha of land or water normalized to the world-averaged productivity from all of the biologically-productive land and water, within a given year" (Čuček et al., 2012). The sum of all the available biologically productive area on earth is roughly equal to approximately 120 million square kilometers (Galli et al., 2011).

The Ecological Footprint (EF) standard was developed by the Global Footprint Network and was designed to ensure that footprint assessments are produced consistently and according to community-proposed best practices. It specifies guidelines aimed at ensuring that EF assessments are conducted in an accurate and transparent manner, according to guidelines on issues such as use of source data, derivation of conversion factors, establishment of study boundaries, and communication of findings (Global Footprint Network, 2009). The main strength of the EF concept is that the results are expressed in an intuitive manner, which assists the public to understand complex environmental issues (Čuček et al., 2012). The results are also scientifically robust, making it a reliable instrument to make humanity's dependence on ecosystems clear (Cerutti et al., 2011).

The main drawback of the EF method is that, while it looks at the environmental aspect of sustainability, it does not measure all environmental parameters (Galli et al., 2011). There are also methodological issues related to the EF concept. EF fails to take into account geographic specificity, generalizing the ecosystem properties by assuming a standardized global ecosystem in terms of averaged productivity (Čuček et al., 2012; Samuel-Fitwi et al., 2012). As such, interactions unique to distinct ecosystems are neglected, which results in a simplified EF with equal environmental impacts, regardless of their origin. In this sense, EF fails to capture the variations inherent in different ecosystems, for example, marine, aquatic or forest ecosystems, each unique in their own way (Samuel-Fitwi et al., 2012). Furthermore, data availability is limited, with uncertainty associated with the available data. Converting the data to area units can also be problematic (Čuček et al., 2012). The EF method is applied over a range of scales from assessments of individual products, and from household to regional and country consumption. It is most effective at aggregate levels (Čuček et al., 2012). Examples of EFs related to food include applications in aquaculture (Kautsky et al., 1997), wine (Niccolucci et al., 2008), general food consumption in China (Chen et al., 2010), wheat production (Kissinger & Gottlieb, 2012), and intensive agriculture (Mózner et al., 2012).

The discussion of the CF and EF methodologies highlights the inadequacies of relying on one environmental indicator. The limited nature of CF and EF methodologies in relation to estimating the environmental sustainability of food processing systems shows that they may be insufficient for full environmental information. When it comes to assessing the environmental impacts of agricultural and food processing systems, many studies claim that methods that consider several environmental indicators are more suited to assessing the complexity of these systems (Cerutti et al., 2011). In addition, alternative production systems must be evaluated in a holistic manner in order to identify the possible shifting of impacts from one field/process to another. As such, the use of a multi-impact assessment tool such as the LCA may be more suited to address the complexities of food production systems (Jungbluth et al., 2012). Consequently, the LCA methodology, as applied to food production systems, is discussed in detail in this chapter.

9.5.3 Life cycle assessment

Life cycle assessment (LCA) is a tool created to assess the environmental impact (e.g. use of resources and the environmental consequence of releases) of a product, process, service or system by taking into account each step in its life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (ISO, 2006a). In this sense, LCA is a "cradle-to-grave" approach, as it begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. While the "cradle-to-grave" approach represents a full LCA, partial LCAs can be completed using variants of this approach. Partial LCAs include "cradle-to-gate," from resource extraction to the factory gate, and "gate-to-gate," looking at particular processes in a supply chain. Figure 9.1 illustrates the life cycle stages that can be considered in an LCA (SIAC, 2006). Input and output data such as emissions, waste, energy consumption, and use of resources are also collected for each unit process (Berlin, 2003). Each stage in the life cycle of the product or process is evaluated from the perspective that they are interdependent, meaning that one operation leads to the next one. By including the impacts throughout the product life cycle, an LCA provides a complete view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection (SIAC, 2006). Up until now, LCA has mainly been used to evaluate the environmental impacts of products and industrial services but a growing number of studies incorporating LCA are focusing on the agri-food production sector.

9.5.3.1 LCA method

The LCA process is a systematic, iterative approach and consists of four components (Figure 9.2).

- **Goal and scope definition**: stating the aim, scope, system boundary, and purpose of the LCA study.
- **Inventory analysis**: compiling an inventory of relevant energy and material inputs, and outputs such as products, by-products, wastes, and environmental releases.
- **Impact assessment**: evaluating the potential environmental impacts associated with the identified inputs, outputs, and releases.
- **Interpretation**: interpreting the results to help decision makers make a more informed decision (SIAC, 2006).

9.5.3.2 Standards

The increasing number of LCA analyses carried out in a broad range of study areas prompted the drafting of international standards, ISO 14040 and ISO 14044, in order to

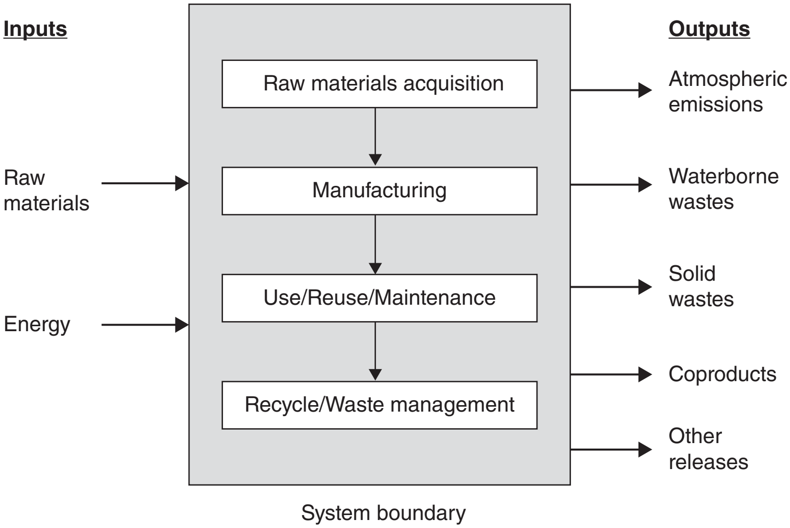

Figure 9.1 Life cycle stages (SAIC, 2006).

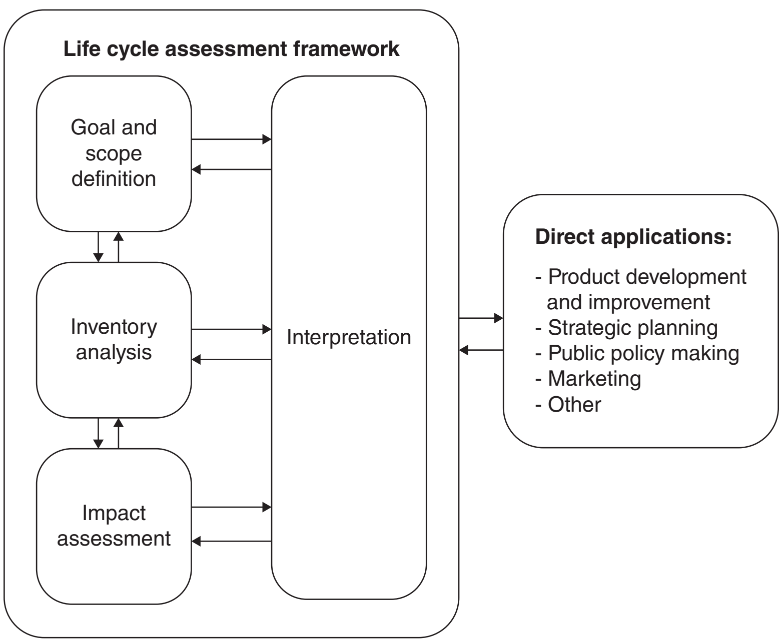

Figure 9.2 Steps of a life cycle assessment (ISO, 2006a).

harmonize the various methodologies that have been used to perform LCAs. The ISO 14040 standard describes the principles and framework for LCA, providing a basic explanation of the standard LCA process (ISO, 2006a). The ISO 14044 standard specifies requirements and provides guidelines for LCA (ISO, 2006b). ISO 14044 outlines the technical requirements, including guidelines on carrying out an LCA, goal and scope definition, inventory analysis, impact assessment, and interpretation. Guidelines are also given on reporting and critical review of the results of an LCA and guidelines for the framework described in ISO 14040. In Britain, a Publicly Available

Specification (PAS) was developed in response to broad community and industry desire for a consistent method for assessing the life cycle GHG emissions of goods and services – PAS 2050:2008 (British Standards Institute, 2008).

9.5.3.3 Goal and scope

The first step in an LCA is potentially the most important and requires the purpose and details of the LCA to be stated in accordance with ISO standards. In this phase, important decisions are made that determine the working plan of the entire LCA (Guinee et al., 2002). The LCA is carried out in line with statements laid out in this section, which defines the purpose of the study and how it is to be carried out. The goal of the study should be clearly stated. The following should be unambiguously stated in the goal: the intended application, the reasons for carrying out the study, the intended audience, whether the results are intended to be used in comparative assertions. The scope of the study should be outlined. The product, process or system is defined and described under the scope. The boundaries of the system are staked out and illustrated by a general input and output flow diagram. All operations that contribute to the life cycle of the product, process, or system are included within the system boundaries. It is essential to determine the functional unit (FU) to which emissions and extractions will then be assigned (Parent & Lavallée, 2011). The FU provides a reference unit to which the inputs and emissions in the inventory are normalized. The FU is often based on the mass of the product under study. However, in food LCA studies, nutritional and economic values of products and land area are also used (Roy et al., 2009). The environmental impacts associated with the FU to be evaluated are identified. Data requirements, assumptions, and limitations of the study should also be stated.

Life cycle assessment requires a number of "value choices" to be made in the goal and scope of the LCA. These choices affect the choosing of the system boundary, functional unit, allocation method, characterization method, etc. Some of these choices will be discussed in more detail further in the chapter.

9.5.3.4 Inventory analysis

The inventory analysis step is the most work-intensive and time-consuming step in an LCA. It involves compiling the required data for the data inventory: all the data relating to the product, process or system being studied, specifically input and output data (Figure 9.3). The qualitative and quantitative data for inclusion in the inventory are collected for each unit process that is included within the system boundary (Guinee et al., 2002). Compiling a data inventory involves identifying and quantifying all input and output flows from the system, including energy, water, and resource usage. Furthermore, releases to the environment from the system are included, such as air emissions (CO_2, CH_4, SO_2, NO_x and CO), water and soil discharges (total suspended solids, biological oxygen demand, chemical oxygen demand, and chlorinated organic compounds) and solid waste generation (municipal solid waste and landfills) (Roy et al., 2009). The collected data are used to quantify the inputs (raw materials, products from other processes, energy, etc.) and outputs (products, emissions, etc.) of unit processes in the LCA. The required data can be measured, calculated or estimated (for product-specific data) and can be obtained from a number of sources including private, government, and university resources (Parent & Lavallée, 2011). LCA databases, which are useful for processes that are not product specific, such as general data on the production of electricity, coal or packaging, are also available and can normally be purchased with LCA software. Data on transport, extraction of raw materials, processing of materials, production of normally used products such as plastic and cardboard, and disposal can normally be found in an LCA database.

The data collected should allow the following questions to be answered:.

- What quantity of energy is required to produce, distribute, and use the product?
- What substances are used during the life phases of the product?
- What are the derivative products, waste, and pollutants released into the environment (water, air, and earth)? (SIAC, 2006)?

9.5.3.5 Impact assessment

The third step involves assessment of the potential human and environmental effects resulting from the various input and output flows to the environment identified in the data inventory. This step relates the energy, water, and raw material usage, along with the environmental releases from the product, process or system, to human and environmental effects (SIAC, 2006). The life cycle impact assessment stage determines which stages and elements of the LCA generate the most impacts and how these impacts may be characterized.

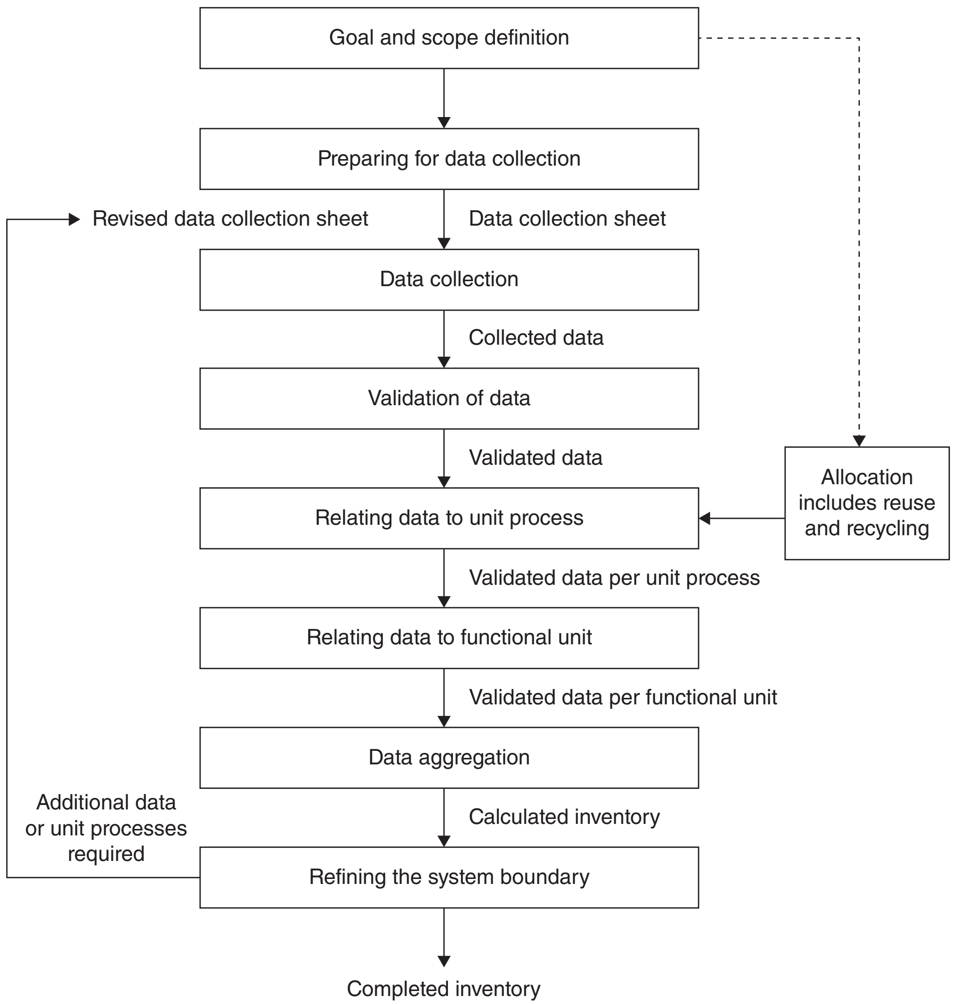

Figure 9.3 Simplified procedures for inventory analysis (ISO, 2006b).

The life cycle impact assessment stage involves the following steps:

- selection of impact categories, category indicators, and characterization models
- assignment of life cycle inventory result to selected impact categories (classification)
- calculation of category indicator results (characterization)

A list of impact categories to be evaluated is defined. There are several impact assessment methods available (detailed under "characterization methods"), each analyzing different impact categories. Common impact assessment categories include global warming, stratospheric ozone destruction, formation of photo-oxidizing (smog) agents, acidification, eutrophication, ecotoxicological impacts, toxicological impact on human beings, use of abiotic resources, use of biotic resources, uses of land. Many of these impacts relate directly to food quality and the concepts of sustainable food security and sustainable agriculture (Parent & Lavallée, 2011).

The results of the inventory analysis, in particular the inventory table, are further processed and assigned to different impact categories, based on the expected types of impacts on the environment. To this end, a list of impact categories is defined, and models for relating the environmental interventions to suitable category indicators for these impact categories are selected (Guinee et al., 2002). This step is known as classification. There are two types of category indicators: mid point and end point. These refer to the distance along the environmental mechanism where the impact is evaluated. According to Bare et al. (2000), mid points are considered to be a point in "the environmental mechanism of a particular impact category, prior to the endpoint, at which characterization factors can be calculated to reflect the relative importance of an emission or extraction in a Life Cycle Inventory." Mid-point indicators include measurements of global warming potential, acidification and eutrophication potential, human and ecotoxicity, etc. End-point indicators reflect issues of concern such as flooding, extinction of species or human lives lost, which occur at the end of the environmental mechanism as a result of global warming, acidification, etc. There is a higher degree of uncertainty related to end-point indicators than mid-point indicators, but end-point results are easier to interpret. Mid-point and end-point indicators are shown in Figure 9.4.

The actual impact assessment results are calculated in the characterization step (Guinee et al., 2002). Characterization involves the assessment of the magnitude of potential impacts of each inventory flow into its corresponding environmental impact (e.g., modeling the potential impact of carbon dioxide and methane on global warming potential, or the impact of sulfur dioxide and ammonia on acidification potential). Characterization provides a way to directly compare the life cycle inventory (LCI) results within each category. Characterization factors are also known as equivalency factors.

There are a number of characterization methods available for both mid-point and end-point characterization. Mid-point methods include:
- CML 2001 (Guinee et al., 2002)
- TRACI 2.0 (Bare, 2011)
- EDIP (Hauschild & Potting, 2003).

End-point methods include:
- Eco-indicator (Goedkoop & Spriensma, 1999)
- Impact 2002+ (Jolliet et al., 2003)
- ReCiPe (Goedkoop et al., 2009).

Normalization of the results allows the expression of potential impacts in ways that can be compared (e.g. comparing the global warming impact of carbon dioxide and methane for the two options). Valuation is a subjective step in which assessment of the relative importance of environmental burdens identified in the classification, characterization, and normalization stages

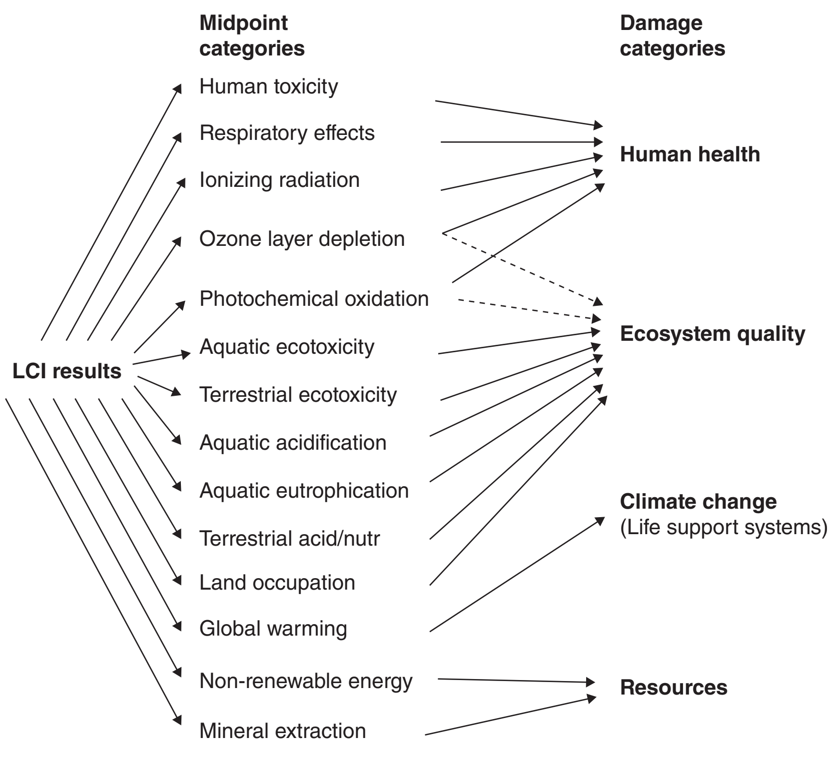

Figure 9.4 Mid-point and end-point indicators (Jolliet et al., 2003).

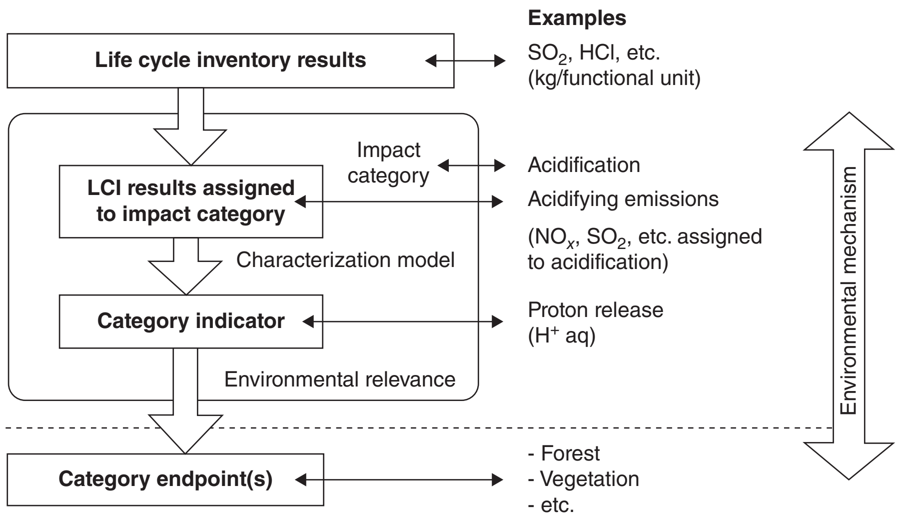

Figure 9.5 Concept of category indicators (ISO, 2006b).

is carried out by weighting them (decided by the stakeholders involved), which allows them to be compared or aggregated (Miettinen & Hämäläinen, 1997). Figure 9.5 outlines the concept of category indicators.

9.5.3.6 Interpretation

The last step in an LCA is the interpretation of the results of the previous three stages in order to draw conclusions that can support a decision or provide a readily understandable result of an LCA. In this step, the data can be analyzed, taking into account assumptions made in the LCA, to assess the quality of the results. During interpretation, the inventory and impact assessment results are discussed together in the case of an LCA, or the inventory only in the case of LCI analysis, and significant environmental issues are identified for conclusions and recommendations consistent with the goal and scope of the study (SIAC, 2006). Interpretation allows for exploration of the areas of the product or process life cycle that could be optimized to reduce environmental impacts and can help identify potential alternative solutions to reduce the environmental impact (Parent & Lavallée, 2011). This may include both quantitative and qualitative measures of improvement, such as changes in product, process and activity design, raw material use, industrial processing, consumer use, and waste management (Roy et al., 2009). Figure 9.6 presents the steps involved in the interpretation phase of an LCA.

9.5.3.7 Life cycle assessment of food products: challenges and applications

Choosing the functional unit (FU) of a food product can be difficult, as food fulfills several functions; it should provide energy and nutrients as well as taste satisfaction. A review by Peacock et al. (2011) found that the FU was not properly identified in many LCA studies, and there was no clear distinction between the FU and the reference flow. The mass of a product is frequently used in LCA studies, but this may not be appropriate for all food products, as it does not take into account the properties of the food. Nutritional values such as protein content and energy content are also commonly used along with economic values (Roy et al., 2009). Other FUs include volume, portions, and pieces of products (Peacock et al., 2011).

The FU is particularly important when comparing the environmental impact of similar food products. According to ISO 14044, in a comparative study, the equivalence of the systems being compared must be determined before the interpreting step in order that the systems can be compared. As a result, the systems must be compared using the same FU (ISO, 2006b).

When analyzing systems that produce multiple products (co-products and by-products), it is very important to allocate the environmental impacts to each of the products in an appropriate manner. Allocation is required in order to determine the quantity of the environmental impacts arising from the entire system, which can be

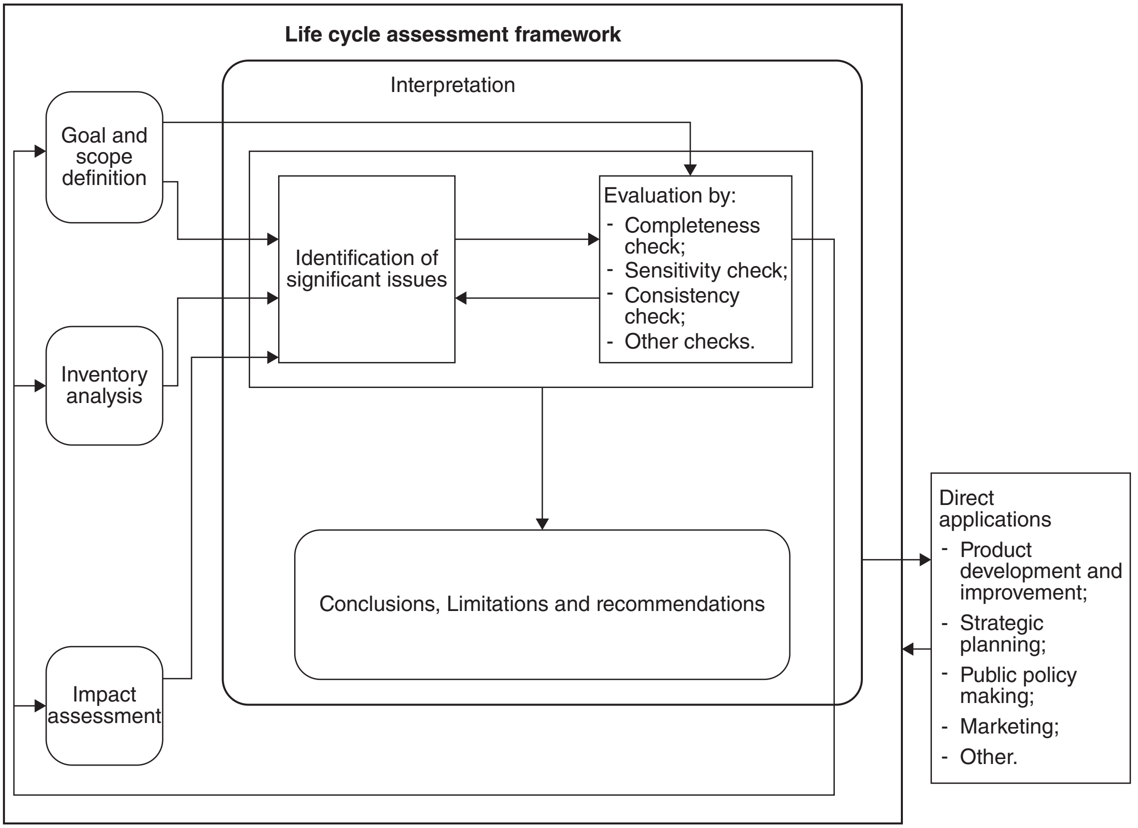

Figure 9.6 Relationships between elements within the interpretation phase with the other phases of life cycle assessment (ISO, 2006b).

apportioned to the individual product in question. Allocation is particularly relevant in food systems where there are often several products produced during a process.

The ISO 14044 standard recommends that allocation should be avoided where possible (ISO, 2006b). This can be achieved by dividing the unit process into subprocesses and collecting the relevant inventory data for the subprocesses, or by system expansion (avoided burden). System expansion involves the expansion of the system boundaries to include the additional functions of the co- or by-products. This can be achieved by identifying an alternative process for the production of the co- or by-product and including it in the expanded boundaries of the original system (Cederberg & Stadig, 2003). If the data inventory exists for this alternative process, it can be subtracted from the inventory of the multi-output process, therefore removing the co- or by-products impact on the final result.

If allocation cannot be avoided then it is necessary to divide the environmental impacts over the different products. The environmental burden can be divided between the products on a mass, energy, physicochemical or economic basis. ISO 14044 has recommended that allocation should reflect underlying physical relationships between inputs and outputs or, in the absence of such knowledge, allocation should reflect other relationships (e.g. economic value). Economic allocation is generally used for food systems, but studies are increasingly using mass and energy contents. Lundie et al. (2007) developed an alternative physicochemical allocation matrix for the dairy industry, which overcomes the issues of mass, process energy, or economic allocations associated with a multiproduct manufacturing plant. This allocation method gives a more realistic evaluation of environmental impact per product.

The use of LCA in the food industry is growing with increasing awareness of the importance of environmental sustainability. LCAs are being applied to a wide range of food products and food production systems. There are several studies that contain comprehensive reviews of LCA studies of food products (Andersson, 2000; de Vries & de Boer, 2010; Milani et al., 2011; Mogensen et al., 2010; Roy et al., 2009). Table 9.1 provides an overview of recent studies. It is clear from this table that LCA studies are being carried out on a wide range of products.

While LCAs have been performed by many food companies, the release of LCA reports to the public is limited due to confidentiality surrounding the production chain. Arla Food, a Danish company, has performed LCA studies on various aspects of its products: dairy products, cheese, and milk packaging (Arla Foods, 2011). Danone (a multinational food product company known as Dannon in the US) has also carried out LCA studies on its products, notably evaluating the energy consumed in producing Evian mineral water and yoghurt (Danone, 2006). More recently, Danone became the first company in Europe to switch to the more environmentally friendly PLA type of packaging for its Activia brand of yoghurt. The decision was based on an LCA study, which determined that switching to this packaging will reduce the packaging carbon footprint by 25% and will use 43% less fossil fuel (Mohan, 2011).

Unilever has implemented LCAs to assist in reducing the environmental impact of its products across its business. Unilever makes use of LCAs in product innovation by comparing new and existing products, in product category analysis and on strategic studies (Unilever, 2011). Examples of Unilever LCA studies include a comparative LCA of butter and margarine consumption (Nilsson et al., 2010) and an estimation of the greenhouse gas emissions associated with Knorr (Milà i Canals et al., 2011).

Life cycle assessments of a food product, process or system are wide and far-reaching. They can identify the processes and materials with the least environmental impact and the optimum combination of energy sources. Weak points (or hotspots) in a system leading to high environmental emissions can be identified using LCAs. As such, LCAs can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle. An LCA can help in identifying the most environmentally friendly packaging and transport options. It is a problem-solving tool that allows the evaluation of alternative products, processes or systems by comparing like with like. As such, LCA can evaluate the differences between conventional and organic agriculture, and fresh, cold, and preserved foods.

Life cycle assessment allows a system to be environmentally optimized in a holistic manner. This ensures system-wide optimization rather than subsystem optimization. For example, when selecting between two rival products, it may appear that product 1 is better for the environment because it generates fewer GHG emissions than product 2. However, after performing an LCA, it might be determined that the first product actually creates larger environmental impacts when measured across different impact categories and across the three media of air, water, and land. Additionally, product 1 may cause more chemical emissions during the manufacturing stage and as such product 2 may be viewed as producing less environmental harm or impact than the first technology because of its lower chemical emissions (SIAC, 2006). LCAs can be especially useful from a marketing point of view for a food processing company by assisting in implementing an ecolabeling scheme, supporting claims of environmental superiority, or producing an environmental product declaration.

Despite the advantages of using LCAs in assessing environmental sustainability, disadvantages associated with the method do exist. It can be difficult to define the system boundary and goal and scope in a consistent and meaningful manner (Tingström & Karlsson, 2006). When carrying out an LCA, it is unavoidable that assumptions about the system being studied are made, simplifying the system into a more manageable model than in reality. Such assumptions may dilute the accuracy of the results (Ritzén et al., 1996). A large quantity of data is required to carry out an LCA of a product. There are often issues with availability of data, along with quality and reliability of data (Ritzén et al., 1996; Tingström & Karlsson, 2006). Furthermore, aggregation of the inventory data into the standardized environmental impact categories can result in a loss of insight into the emissions from the process or system (Balkema et al., 2002).

The results obtained from the LCA analysis are neither spatially or temporally specific. If using an LCA in process or product development, this can be an issue, as information on temporal and spatial aspects is often required in decision-making processes by the stakeholders involved (Herrchen & Klein, 2000). Finally, LCAs may not be useful in product development, as carrying out a full LCA on a new product is costly, time consuming, and difficult (Ritzén et al., 1996; Tingström & Karlsson, 2006).

Table 9.1 Summary of recent Life Cycle Assessment studies on various food production systems

Ref	Location	Product	By/co-product(s)	Functional Unit	Allocation	GWP	En	OG	AP	EP	LU	H_2O	Tox	OD	POCP	Oth
Meat, fish and dairy products																
Beauchemin (2010)	Canada	Beef	None considered	1 kg of beef produced	Not considered	x										
Pelletier (2010)	USA	Beef	Crop co-products (for feed)	1 kg of beef produced	Gross chemical energy content	x	x			x	x					
Pelletier (2008)	Canada	Broiler production	Feed	1 live weight ton of broiler poultry	Gross chemical energy content	x	x		x	x						x
Flysjo (2011)	New Zealand and Sweden	Milk	Surplus calves, meat from culled dairy cows and manure	1 kg of energy corrected milk (ECM) (calculated according to Sjaunja et al. (1990) to correct for fat and protein) provided at the farm gate in NZ and SE, respectively, including all by-products	Economic	x										
Castanheira (2010)	Portugal	Milk	Meat from culled dairy cows	1 ton of raw milk ready to be delivered at the farm gate	Economic	x			x	x						x
van Middelaar (2011)	Netherlands	Cheese	Milk	1 kg cheese	Economic	x	x				x					
Vasquez-Rowe (2011)	Spain	Hake fillets	None considered	500 g of raw gutted fresh hake fillet reaching the household of an average consumer in the year 2008	Not considered	x			x	x						x
Hospido (2006)	Spain	Canned tuna	None considered	1 ton of raw frozen tuna entering the factory	Economic	x			x	x						x
Pelletier (2010)	USA and Netherlands	Indonesian tilapia	Fish trimmings	1 ton of frozen tilapia fillets from lake-pen cultured fish in Indonesia to market ports in Rotterdam and Chicago	Gross energy content	x	x		x	x						x
Crops, vegetables and fruit																
Meisterling (2009)	USA	Conventional v organic wheat	None considered	0.67 kg of whole-wheat flour	Not considered	x	x									
Blengini (2009)	Italy	Rice	Residuals	1 kg of refined rice packed and delivered to the supermarket	Economic	x	x		x	x		x			x	x
Bevilacqua (2007)	Italy	Pasta	Subproducts	0.5 kg package of a popular brand of durum wheat pasta sold in the Italian market	Not considered	x	x		x	x			x			x
Liu (2010)	China	Chinese pears	None considered	1 ton of pears for direct human consumption, delivered to the point-of-sale	Not considered	x	x									

Beccali (2010)	Italy	Citrus-based products	Products	1 kg of each final product delivered by the manufacturer to distribution centres in Italy, Central Europe, the United States and Japan (oranges essential oil, oranges natural juice, oranges concentrated juice, lemons essential oil, lemons natural juice, lemons concentrated juice)	Combined mass and economic	x	x		x	x		x			x	
Martinez-Blano (2011)	Spain	Tomatos	Compost	1 ton of commercial tomato	System expansion	x	x		x	x						x
Romero-Gamez (2012)	Spain	Green beans	None considered	1 kg of commercial green beans	Not considered	x			x	x			x		x	x
Karakaya (2011)	Turkey	Tomato products	None considered	Several products	Not considered	x	x									
Meals																
Davis (2010)	Spain and Sweden	4 protein rich meals (for animals)	Several	one meal served at the table in a household, in two different countries, Sweden and Spain	Economic	x	x		x	x				x	x	
Calderon (2010)	Spain	Ready meals	None considered	1 kg of finished product ready to be consumed	Not considered	x			x	x	x		x			x
Zufia (2008)	Spain	Industrial cooked dish	None considered	2 kg tray of pasteurized tuna with tomato	Not considered	x			x	x			x	x		x
Beverages																
Humbert (2009)	Switzerland	Coffee	None considered	provide a 1 dl cup of coffee ready to be drunk at the consumer's home	Not considered	x	x					x				
Pizzigallo (2008)	Italy	Wine	None considered	1 ton of final product	Not considered			x								
Gazulla (2010)	Spain	Wine	Pomace, lees, syrup	0.75 l of wine	Economic	x			x	x					x	
Cordella (2008)	Italy	Beer	Roots, spent grains and yeast excess	1 l of beer and the fraction of packaging allocated to such a litre (1/20 of a 20 L steel keg or three 33 cL glass bottles)	System expansion	x	x		x		x		x			x
Water Use																
Ridoutt (2010b)	Australia	Water footprint of skimmed milk powder	*	1 kg of skim milk powder in the temperate South Gippsland region of Victoria	Physiochemical and economic							x				

(Continued)

Table 9.1 (*Continued*)

Ref	Location	Product	By/co-product(s)	Functional Unit	Allocation	GWP	En	OG	AP	EP	LU	H_2O	Tox	OD	POCP	Oth
Ridoutt (2010a)	Australia	Water footprint of food waste (mango)	Fresh mango	consumption of 1 kg of fresh mango by an Australian household	Economic							x				
Others																
Nilsson (2010)	UK, Germany, France	Margarine and butter	Skim milk, waste for feed etc.	500 g of packaged butter/margarine intended for use as a spread, delivered to the manufacturer's distribution centre in each country	Economic, mass and others	x	x		x	x	x				x	
Avraamides (2008)	Cyprus	Olive oil	Waste and pomace	1 l of extra virgin olive oil extracted	Economic			x								x
Kim (2010)	Republic of Korea	Waste disposal	Animal feeds and composts from food wastes	by-products from dry feeding, wet feeding, composting, and landfilling of 1 ton of food wastes respectively	System expansion	x										
Pasqualino (2011)	Spain	Beverage packaging	None considered	packaging required to contain 1 l of beverage	Not considered	x	x									
Williams (2011)	Sweden	Packaging and food losses (ketchup, bread, milk, cheese, beef)	None considered	1 kg of purchased food	Not considered	x	x		x	x						

GWP – Global Warming Potential, En – Energy use, OG – Other Gases, AP – Acidification Potential, EP – Eutrophication Potential, LU – Land Use, H_2O – Water use, OD – Stratospheric ozone depletion, POCP – Photochemical ozone creation potential.

9.5.3.8 Life cycle assessment software and databases

The two main licensed software products for LCA are Simapro, developed by Pré Consultants, and GaBi, developed by PE International (GaBi, 2010). These software products are flexible and can be used to carry out LCAs on any product or systems, including food production and processing systems. The software packages differ based on their user interfaces, and methods of modeling and analyzing the life cycle. Both software packages come with a number of databases containing inventory data which can be used for background for the food system; examples of background data include electricity from the grid and mains water supply. Demo versions of these software products are available with limited access to databases.

There are a number of databases available containing life cycle inventory data for a range of products, processes, and systems. The unit processes from these databases are used in the LCA software in building the system being studied. These databases can provide general data for a wide range of systems but there are a few databases with data specifically concerning food production. The Danish LCA food database contains environmental data on processes in food product chains and on food products at different stages of their production (Nielsen et al., 2003). The Ecoinvent database developed by the Swiss Centre for Life-Cycle Inventories also contains European and Swiss data for agricultural production (Swiss Centre for Life-Cycle Inventories, 2007). The US LCI database developed by the National Renewable Energy Lab contains data for the US (NREL, 2008). Each of these databases is included with Simapro and GaBi when a license is purchased.

9.6 Conclusion

Food safety and quality will remain at top priority for food processors, especially due to increasing numbers of authenticity, adulteration, and safety issues in food products. However, environmental sustainability is becoming increasingly important to companies. The co-management of safety, quality, and sustainability issues will ensure that quality and safety are maintained while ensuring improved sustainability. One of the challenges in achieving this goal will be enabling companies in making informed decisions. Food processors should not only assess the impact of processing but also the wider supply and distribution chains, and end of life of the product or packaging. The use of various sustainability assessment methodologies should assist in achieving this goal.

References

Andersson K (2000) LCA of food products and production systems. *International Journal of Life Cycle Assessment* **5**(4): 239–248.

Aneke M, Agnew B, Underwood C, Wu H, Masheiti S (2012) Power generation from waste heat in a food processing application. *Applied Thermal Engineering* **36**, 171–180.

Arla Foods (2011) *Environment and Climate Log*. Leeds: Arla Foods.

Avraamides M, Fatta D (2008) Resource consumption and emissions from olive oil production: a life cycle inventory case study in Cyprus. *Journal of Cleaner Production* **16**(7): 809–821.

Baldwin CJ (2009) Introduction. In: *Sustainability in the Food Industry*. Ames, IA: Wiley-Blackwell, pp. xiii–xvi.

Balkema AJ, Preisig HA, Otterpohl R, Lambert FJD (2002) Indicators for the sustainability assessment of wastewater treatment systems. *Urban Water* **4**(2): 153–161.

Banks CJ, Salter AM, Heaven S, Riley K (2011) Energetic and environmental benefits of co-digestion of food waste and cattle slurry: a preliminary assessment. *Resources, Conservation and Recycling* **56**(1): 71–79.

Bare J (2011) TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0) *Clean Technologies and Environmental Policy* 1–10.

Bare J, Hofstetter P, Pennington D, de Haes H (2000) Midpoints versus endpoints: the sacrifices and benefits. *International Journal of Life Cycle Assessment* **5**(6): 319–326.

Barton P, Hughes Jr RE, Hussein MM (1992) Supercritical carbon dioxide extraction of peppermint and spearmint. *Journal of Supercritical Fluids* **5**(3): 157–162.

Beauchemin KA, Henry Janzen H, Little SM, McAllister TA, McGinn SM (2010) Life cycle assessment of greenhouse gas emissions from beef production in western Canada: a case study. *Agricultural Systems* **103**(6): 371–379.

Beccali M, Cellura M, Iudicello M, Mistretta M (2010) Life cycle assessment of Italian citrus-based products. *Sensitivity analysis and improvement scenarios. Journal of Environmental Management* **91**(7): 1415–1428.

Berk Z (2009) *Food Process Engineering and Technology*. Burlington, VA: Academic Press.

Berlin J (2003) Life cycle assessment (LCA): an introduction. In: Mattson B, Sonesson U (eds) *Environmentally-Friendly Food Processing*. Cambridge: Woodhead Publishing Limited.

Bevilacqua M, Braglia M, Carmignani G, Zammori FA (2007) Life cycle assessment of pasta production in Italy. *Journal of Food Quality* **30**(6): 932–952.

Blengini GA, Busto M (2009) The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). *Journal of Environmental Management* **90**(3): 1512–1522.

Boye JI, Arcand Y (2012) *Green Technologies in Food Production and Processing*. New York: Springer.

British Standards Institute (2008) *PAS 2050:2008 – Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*. London: British Standards Institute.

British Standards Institute (2011) *PAS 2050:2011 – Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*. London: British Standards Institute.

Calderon LA, Iglesias L, Laca A, Herrero M, Diaz M (2010) The utility of Life Cycle Assessment in the ready meal food industry. *Resources, Conservation and Recycling* **54**(12): 1196–1207.

Casani S, Rouhany M, Knøchel S (2005) A discussion paper on challenges and limitations to water reuse and hygiene in the food industry. *Water Research* **39**(6): 1134–1146.

Casey JW, Holden NM (2005) Analysis of greenhouse gas emissions from the average Irish milk production system. *Agricultural Systems* **86**(1): 97–114.

Castanheira ÉG, Dias AC, Arroja L, Amaro R (2010) The environmental performance of milk production on a typical Portuguese dairy farm. *Agricultural Systems*,**103**(7): 498–507.

Caton PA, Carr MA, Kim SS, Beautyman MJ (2010) Energy recovery from waste food by combustion or gasification with the potential for regenerative dehydration: a case study. *Energy Conversion and Management* **51**(6): 1157–1169.

Cederberg C, Stadig M (2003) System expansion and allocation in life cycle assessment of milk and beef production. *International Journal of Life Cycle Assessment* **8**(6): 350–356.

Cerutti AK, Bruun S, Beccaro GL, Bounous G (2011) A review of studies applying environmental impact assessment methods on fruit production systems. *Journal of Environmental Management* **92**(10): 2277–2286.

Cheigh CI, Chung EY, Chung MS (2012) Enhanced extraction of flavanones hesperidin and narirutin from Citrus unshiu peel using subcritical water. *Journal of Food Engineering* **110**(3): 472–477.

Chen D, Gao W, Chen Y, Zhang Q (2010) Ecological footprint analysis of food consumption of rural residents in China in the latest 30 years. *Agriculture and Agricultural Science Procedia* **1** (0): 106–115.

Clark JH (2010) Introduction to green chemistry. In: Proctor A (ed) *Alternatives to Conventional Food Processing*. London: Royal Society of Chemistry.

Cooke P (2008) Legislation and economic issues regarding water and energy management in food processing. In: Klemeš J, Smith R, Kim JK (eds) *Handbook of Water and Energy Management in Food Processing*. Cambridge: Woodhead Publishing, pp. 3–28.

Cordella M, Tugnoli A, Spadoni G, Santarelli F, Zangrando T (2008) LCA of an Italian lager beer. *International Journal of Life Cycle Assessment* **13**(2): 133–139.

Čuček L, Klemeš JJ, Kravanja Z (2012) A review of footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production* **34**, 9–20.

Curry N, Pillay P (2012) Biogas prediction and design of a food waste to energy system for the urban environment. *Renewable Energy* **41**(0): 200–209.

Danone (2006) *Sustainability Report*. Paris: Danone.

Davis J, Sonesson U, Baumgartner DU, Nemecek T (2010) Environmental impact of four meals with different protein sources: case studies in Spain and Sweden. *Food Research International* **43**(7): 1874–1884.

de Haan AB, de Graauw J, Schaap JE, Badings HT (1990) Extraction of flavors from milk fat with supercritical carbon dioxide. *Journal of Supercritical Fluids* **3**(1): 15–19.

de Vries M, de Boer IJM (2010) Comparing environmental impacts for livestock products: a review of life cycle assessments. *Livestock Science* **128**(1–3): 1–11.

Dole (2008) *Dole Announces Conversion of Farm Equipment to Bio-Diesel Fuel*. www.thefreelibrary.com/Dole+Announces+Conversion+of+Farm+Equipment+to+Bio-Diesel+Fuel.-a0173797625, accessed 13 November 2013.

Doneanu C, Anitescu G (1998) Supercritical carbon dioxide extraction of Angelica archangelica L. root oil. *Journal of Supercritical Fluids* **12**(1): 59–67.

Drastig K, Prochnow A, Kraatz S, Klauss H, Plöchl M (2010) Water footprint analysis for the assessment of milk production in Brandenburg (Germany). *Advances in Geosciences* **27**, 65–70.

Eikani MH, Golmohammad F, Rowshanzamir S (2007) Subcritical water extraction of essential oils from coriander seeds (Coriandrum sativum L.). *Journal of Food Engineering* **80**(2): 735–740.

El-Mashad HM, Zhang R (2010) Biogas production from co-digestion of dairy manure and food waste. *Bioresource Technology* **101**(11): 4021–4028.

Energy Information Administration (EIA) (2011) *International Energy Outlook 2011*. DOE/EIA–0484(2011). Washington, DC: Energy Information Administration.

EU Joint Research Centre (2013) European IPPC Bureau. http://eippcb.jrc.ec.europa.eu/, accessed 19 November 2013.

European Commission (1999) *The Landfill of Waste*. www.central2013.eu/fileadmin/user_upload/Downloads/Document_Centre/OP_Resources/Landfill_Directive_1999_31_EC.pdf, accessed 13 November 2013.

European Commission (2008) *Integrated Pollution Prevention & Control Directive*. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31996L0061:en:HTML, accessed 19 November 2013.

European Commission (2010) *The Industrial Emissions Directive*. http://ec.europa.eu/environment/air/pollutants/stationary/ied/legislation.htm, accessed 13 November 2013.

European Commission (2011) *Determining Transitional Union-Wide Rules for Harmonised Free Allocation of Emission Allowances Pursuant to Article 10a of Directive 2003/87/Ec of the European Parliament and of the Council (Notified Under Document C(2011) 2772)*. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:130:FULL:EN:PDF, accessed 19 November 2013.

European Commission (2013) *Auctioning*. http://ec.europa.eu/clima/policies/ets/cap/auctioning/index_en.htm, accessed 19 November 2013.

Fagan CC, Castillo M, O'Donnell CP, O'Callaghan DJ, Payne FA (2008) On-line prediction of cheese making indices using backscatter of near infrared light. *International Dairy Journal* **18**(2): 120–128.

Flysjö A, Henriksson M, Cederberg C, Ledgard S, Englund JE (2011) The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agricultural Systems* **104**(6): 459–469.

GaBi (2010) *GaBi 4 dataset documentation for the software system and databases*. Leinfelden-Echterdingen: University of Stuttgart and PE International GmbH.

Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S (2011) Integrating Ecological, Carbon and Water Footprint: Defining the "Footprint Family" and its Application in Tracking Human Pressure on the Planet. One Planet Economy Network. www.oneplaneteconomynetwork.org/resources/programme-documents/WP8_Integrating_Ecological_Carbon_Water_Footprint.pdf, accessed 13 November 2013.

Gazulla C, Raugei M, Fullana-i-Palmer P (2010) Taking a life cycle look at crianza wine production in Spain: where are the bottlenecks? *International Journal of Life Cycle Assessment* **15**(4): 330–337.

Gerbens-Leenes PW, Moll HC, Schoot Uiterkamp AJM (2003) Design and development of a measuring method for environmental sustainability in food production systems. *Ecological Economics* **46**(2): 231–248.

Global Footprint Network (2009) Ecological Footprint Standards. www.footprintnetwork.org/fr/index.php/blog/af/participate_in_the_2012_ecological_footprint_standards, accessed 13 November 2013.

Global Footprint Network (2012) Glossary. http://www.footprintnetwork.org/en/index.php/GFN/page/glossary/, accessed 13 November 2013.

Goedkoop M, Spriensma R (1999) *The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment*. Amersfoot, Netherlands: PRé Consultants.

Goedkoop M, Heijungs R, Huijbregts M et al. (2009) *ReCiPe 2008. A Life-Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators of the Midpoint and Entry Level*. Amersfoot, Netherlands: PRé Consultants.

Guinee JB, Gorree M, Heijungs R et al. (2002) *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. 1: LCA in perspective. 2a: Guide. 2b: Operational Annex. 3: Scientific background*. Dordrecht: Kluwer Academic Publishers.

Hall GM, Howe J (2012) Energy from waste and the food processing industry. *Process Safety and Environmental Protection* **90**(3): 203–212.

Hassas-Roudsari M, Chang PR, Pegg RB, Tyler RT (2009) Antioxidant capacity of bioactives extracted from canola meal by subcritical water, ethanolic and hot water extraction. *Food Chemistry* **114**(2): 717–726.

Hauschild M, Potting J (2003) *Spatial Differentiation in Life Cycle Impact Assessment – The EDIP 2003 Methodology*. Lyngby, Denmark: Institute for Product Development, Technical University of Denmark.

He L, Zhang X, Xu H et al. (2012) Subcritical water extraction of phenolic compounds from pomegranate (Punica granatum L.) seed residues and investigation into their antioxidant activities with HPLC-ABTS + assay. *Food and Bioproducts Processing* **90**(2): 215–223.

Henningsson S, Hyde K, Smith A, Campbell M (2004) The value of resource efficiency in the food industry: a waste minimisation project in East Anglia, UK. *Journal of Cleaner Production* **12**(5): 505–512.

Herrchen M, Klein W (2000) Use of the life-cycle assessment (LCA) toolbox for an environmental evaluation of production processes. *Pure and Applied Chemistry* **72**(7): 1247–1252.

Hillier J, Hawes C, Squire G, Hilton A, Wale S, Smith P (2009) The carbon footprints of food crop production. *International Journal of Agricultural Sustainability* **7**(2): 107–118.

Hoogland CT, de Boer J, Boersema JJ (2007) Food and sustainability: do consumers recognize, understand and value on-package information on production standards? *Appetite* **49**(1): 47–57.

Humbert S, Loerincik Y, Rossi V, Margni M, Jolliet O (2009) Life cycle assessment of spray dried soluble coffee and comparison with alternatives (drip filter and capsule espresso). *Journal of Cleaner Production* **17**(15): 1351–1358.

Ike M, Inoue D, Miyano T et al. (2010) Microbial population dynamics during startup of a full-scale anaerobic digester treating industrial food waste in Kyoto eco-energy project. *Bioresource Technology* **101**(11): 3952–3957.

ISO (2006a) EN ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework. www.iso.org/iso/catalogue_detail.htm?csnumber=37456, accessed 13 November 2013.

ISO (2006b) EN ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines. www.iso.org/iso/catalogue_detail?csnumber=38498, accessed 13 November 2013.

ISO (2012) ISO/TS 14067. Carbon footprint of products. Requirements and guidelines for quantification and communication. www.iso.org/iso/catalogue_detail?csnumber=59521, accessed 13 November 2013.

Jaffry, S, Pickering, H, Ghulam, Y, Whitmarsh, D, Wattage, P (2004) Consumer choices for quality and sustainability labelled seafood products in the UK. *Food Policy*, **29**(3): 215–228.

Jolliet O, Margni M, Charles R et al. (2003) IMPACT 2002+: a new life cycle impact assessment methodology. *International Journal of Life Cycle Assessment* **8**(6): 324–330.

Jung S, Tonello Samson C, Lamballerie M (2011) High hydrostatic pressure food processing. In: Proctor A (ed) *Alternatives to Conventional Food Processing*. London: Royal Society of Chemistry, pp. 254–306.

Jungbluth N, Büsser S, Frischknecht R, Flury K, Stucki M (2012) Feasibility of environmental product information based on life cycle thinking and recommendations for Switzerland. *Journal of Cleaner Production* **28**(0): 187–197.

Karakaya A, Özilgen M (2011) Energy utilization and carbon dioxide emission in the fresh, paste, whole-peeled, diced, and juiced tomato production processes. *Energy* **36**(8): 5101–5110.

Kautsky N, Berg H, Folke C, Larsson J, Troell M (1997) Ecological footprint for assessment of resource use and development limitations in shrimp and tilapia aquaculture. *Aquaculture Research* **28**, 753–766.

Kearney J (2010) Food consumption trends and drivers. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**(1554): 2793–2807.

Kettle Foods (2009) *Sustainability*. Salem, OR: Kettle Foods.

Khajeh M, Yamini Y, Sefidkon F, Bahramifar N (2004) Comparison of essential oil composition of Carum copticum obtained by supercritical carbon dioxide extraction and hydrodistillation methods. *Food Chemistry* **86**(4): 587–591.

Kim JK, Smith R (2008) Methods to minimise water use in food processing. In: Klemeš J, Smith R, Kim JK (eds) *Handbook of Water and Energy Management in Food Processing*. Cambridge: Woodhead Publishing, pp. 113–135.

Kim MH, Kim JW (2010) Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. *Science of the Total Environment* **408**(19): 3998–4006.

Kissinger M, Gottlieb D (2012) From global to place oriented hectares – the case of Israel's wheat ecological footprint and its implications for sustainable resource supply. *Ecological Indicators* **16**, 51–57.

Ko,MJ, Cheigh CI, Cho SW, Chung MS (2011) Subcritical water extraction of flavonol quercetin from onion skin. *Journal of Food Engineering* **102**(4): 327–333.

Kosseva R, Steve T (2009) Processing of food wastes. In: Taylor S (ed) *Advances in Food and Nutrition Research* **58**, 57–136.

Lai CM, Ke GR, Chung MY (2009) Potentials of food wastes for power generation and energy conservation in Taiwan. *Renewable Energy* **34**(8): 1913–1915.

Laufenberg G, Kunz,B, Nystroem M (2003) Transformation of vegetable waste into value added products: (A) the upgrading concept; (B) practical implementations. *Bioresource Technology* **87**(2): 167–198.

Law R, Harvey A, Reay D (2013) Opportunities for low-grade heat recovery in the UK food processing industry. *Applied Thermal Engineering* **53**(2): 188–196.

Liu Y, Langer V, Høgh-Jensen H, Egelyng H (2010) Life cycle assessment of fossil energy use and greenhouse gas emissions in Chinese pear production. *Journal of Cleaner Production* **18** (14): 1423–1430.

Lundie S, Dennien G, Morain M, Jones M (2007) Generation of an industry-specific physico-chemical allocation matrix. *Application in the dairy industry and implications for systems analysis. International Journal of Life Cycle Assessment* **12**(2): 109–117.

Manley JB, Anastas PT, Cue Jr BW (2008) Frontiers in green chemistry: meeting the grand challenges for sustainability in R&D and manufacturing. *Journal of Cleaner Production* **16** (6): 743–750.

Marechal F, Muller D (2008) Energy management methods for the food industry. In: Klemeš J, Smith R, Kim JK (eds) *Handbook of Water and Energy Management in Food Processing*. Cambridge: Woodhead Publishing, pp. 221–255.

Martínez-Blanco J, Muñoz P, Antón A, Rieradevall J (2011) Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. *Journal of Cleaner Production* **19**(9–10): 985–997.

Meisterling K, Samaras C, Schweizer V (2009) Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production* **17**(2): 222–230.

Miettinen,P, Hämäläinen RP (1997) How to benefit from decision analysis in environmental life cycle assessment (LCA). *European Journal of Operational Research* **102**(2): 279–294.

Milà i Canals L, Sim S, García-Suárez T et al. (2011) Estimating the greenhouse gas footprint of Knorr. *International Journal of Life Cycle Assessment* **16**(1): 50–58.

Milani FX, Nutter D, Thoma G (2011) Invited review: environmental impacts of dairy processing and products: a review. *Journal of Dairy Science* **94**(9): 4243–4254.

Milman A, Short A (2008) Incorporating resilience into sustainability indicators: an example for the urban water sector. *Global Environmental Change* **18**(4): 758–767.

Mogensen L, Hermansen J, Halberg N, Dalgaard R (2010) Life cycle assessment across the food supply chain. In: Baldwin C (ed) *Sustainability in the Food Industry*. Ames, IA: Wiley-Blackwell.

Mohan,A (2011) Danone first to switch to PLA for yoghurt cup in Germany. www.observatorioplastico.com/detalle_noticia.php?no_id=160079&seccion=reciclado&id_categoria=80001, accessed 13 November 2013.

Mózner Z, Tabi A, Csutora M (2012) Modifying the yield factor based on more efficient use of fertilizer – the environmental impacts of intensive and extensive agricultural practices. *Ecological Indicators* **16**(0): 58–66.

Mustafa A, Turner C (2011) Pressurized liquid extraction as a green approach in food and herbal plants extraction: a review. *Analytica Chimica Acta* **703**(1): 8–18.

My Dieu T (2009) Food processing and food waste. In: Baldwin C (ed) *Sustainability in the Food Industry*. Ames, IA: Wiley-Blackwell, pp. 23–60.

National Renewable Energy Laboratory (NREL) (2008) *US Life-Cycle Inventory Database V 1.6.0*. www.nrel.gov/lci/database/, accessed 19 November 2013.

Niccolucci V, Galli A, Kitzes J, Pulselli RM, Borsa S, Marchettini N (2008) Ecological Footprint analysis applied to the production of two Italian wines. *Agriculture, Ecosystems and Environment* **128**(3): 162–166.

Nielsen P, Nielsen A, Weidema B, Dalgaard R, Halberg N (2003) LCA food data base. www.lcafood.dk.

Nilsson K, Flysjö A, Davis J, Sim S, Unger N, Bell S (2010) Comparative life cycle assessment of margarine and butter consumed in the UK, Germany and France. *International Journal of Life Cycle Assessment* **15**(9): 916–926.

Oliveira AL, Kamimura ES, Rabi JA (2009) Response surface analysis of extract yield and flavour intensity of Brazilian cherry (Eugenia uniflora L.) obtained by supercritical carbon dioxide extraction. *Innovative Food Science and Emerging Technologies* **10**(2): 189–194.

Ozel MZ, Gogus F, Lewis AC (2003) Subcritical water extraction of essential oils from Thymbra spicata. *Food Chemistry* **82**(3): 381–386.

Pap N, Pongrácz E, Myllykoski LRK (2004) Waste minimization and utilization in the food industry: processing of arctic berries, and extraction of valuable compounds from juice – processing by- products. *Proceedings of the Waste Minimization and Resources Use Optimization Conference*, 10 June, University of Oulu, Finland. Oulu: Oulu University Press, pp. 159–168.

Parent G, Lavallée S (2011) LCA potentials and limits within a sustainable agri-food statutory framework. In: Behnassi M, Draggan S, Yaya S (eds) *Global Food Insecurity – Rethinking Agricultural and Rural Development Paradigm and Policy*. Netherlands: Springer, pp .161–171.

Pasqualino J, Meneses M, Castells F (2011) The carbon footprint and energy consumption of beverage packaging selection and disposal. *Journal of Food Engineering* **103**(4): 357–365.

Peacock N, de Camillis C, Pennington D et al. (2011) Towards a harmonised framework methodology for the environmental assessment of food and drink products. *International Journal of Life Cycle Assessment* **16**(3): 189–197.

Pelletier N (2008) Environmental performance in the US broiler poultry sector: life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. *Agricultural Systems* **98**(2): 67–73.

Pelletier N, Tyedmers P (2010) Life cycle assessment of frozen tilapia fillets from Indonesian lake-based and pond-based intensive aquaculture systems. *Journal of Industrial Ecology* **14**(3): 467–481.

Pelletier N, Pirog R, Rasmussen R (2010) Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agricultural Systems* **103**(6): 380–389.

Pirog R, Champion B, Crosby T, Kaplan S, Rasmussen R (2009) Distribution. In: Baldwin C (ed) *Sustainability in the Food Industry*. Ames, IA: Wiley-Blackwell, pp. 61–100.

Pizzigallo ACI, Granai C, Borsa S (2008) The joint use of LCA and emergy evaluation for the analysis of two Italian wine farms. *Journal of Environmental Management* **86**(2): 396–406.

Plassmann K, Edwards-Jones G (2009) Where Does the Carbon Footprint Fall? Developing a Carbon Map of Food Productio*n*. London: IIED.

Plessas S, Koliopoulos D, Kourkoutas Y et al. (2008) Upgrading of discarded oranges through fermentation using kefir in food industry. *Food Chemistry* **106**(1): 40–49.

Reay D (2008) Heat recovery in the food industry. In: Klemeš J, Smith R, Kim JK (eds) *Handbook of Water and Energy Management in Food Processing*. Cambridge: Woodhead Publishing, pp. 544–569.

Rees WE (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization* **4**(2): 121–130.

Ridoutt BG, Juliano P, Sanguansri P, Sellahewa J (2010a) The water footprint of food waste: case study of fresh mango in Australia. *Journal of Cleaner Production* **18**(16–17): 1714–1721.

Ridoutt BG, Williams SRO, Baud S, Fraval S, Marks N (2010b) Short communication: the water footprint of dairy products: case study involving skim milk powder. *Journal of Dairy Science* **93**(11): 5114–5117.

Ritzén S, Hakelius C, Norell M (1996) Life-cycle assessment, implementation and use in industry. In: *Nord-Design '96*. Helsinki, Finland.

Romero-Gámez M, Suárez-Rey EM, Antón A, Castilla N, Soriano T (2012) Environmental impact of screenhouse and open-field cultivation using a life cycle analysis: the case study of green bean production. *Journal of Cleaner Production* **8**, 63–69.

Röös E, Sundberg C, Hansson PA (2010) Uncertainties in the carbon footprint of food products: a case study on table potatoes. *International Journal of Life Cycle Assessment* **15** (5): 478–488.

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. *Journal of Dairy Science* **93**(3): 1266–1282.

Roy P, Nei D, Orikasa T et al. (2009) A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering* **90**(1): 1–10.

Sahota A, Haumann B, Givens H, Baldwin CJ (2009) Ecolabeling and consumer interest in sustainable products. In: Baldwin C (ed) *Sustainability in the Food Industry*. Ames, IA: Wiley-Blackwell, pp. 159–184.

SAIC (2006) *Life Cycle Assessment: Principles and Practice*. US EPA. 68–C02–067. McLean, VA: SAIC.

Samuel-Fitwi B, Wuertz S, Schroeder JP, Schulz C (2012) Sustainability assessment tools to support aquaculture development. *Journal of Cleaner Production* **32**(0): 183–192.

Schaub SM, Leonard JJ (1996) Composting: an alternative waste management option for food processing industries. *Trends in Food Science and Technology* **7**(8): 263–268.

Sellahewa JN, Martindale W (2010) The impact of food processing on the sustainability of the food supply chain. *Aspects of Applied Biology*, **102**.

Shi J, Xue SX, Ma Y et al. (2012) Green separation technologies in food processing: supercritical CO2 fluid and subcritical water extraction. In: Boye J, Arcand Y (eds) *Green Technologies in Food Production and Processing*. New York: Springer, pp. 239–272.

Singh PP, Saldana MDA (2011) Subcritical water extraction of phenolic compounds from potato peel. *Food Research International* **44**(8): 2452–2458.

Swiss Centre for Life-Cycle Inventories (2007) Ecoinvent data v2.0 ecoinvent reports No. 1-25. Dübendorf: Swiss Centre for Life-Cycle Inventories.

Tello J, Viguera M, Calvo L (2011) Extraction of caffeine from Robusta coffee (Coffea canephora var. Robusta) husks using supercritical carbon dioxide. *Journal of Supercritical Fluids* **59**(0): 53–60.

Tingström J, Karlsson R (2006) The relationship between environmental analyses and the dialogue process in product development. *Journal of Cleaner Production* **14**(15–16): 1409–1419.

UK Department of Energy and Climate Change (2012) *Modified UK National Implementation Measures for Phase III of the EU Emissions Trading System*. London: Department of Energy and Climate Change

Unilever (2011) *Lifecycle Assessment*. London: Unilever.

United Nations (1987) *Our Common Future*. Report of the World Commission on Environment and Development. New York: United Nations.

van Middelaar CE, Berentsen PBM, Dolman MA, de Boer IJM (2011) Eco-efficiency in the production chain of Dutch semi-hard cheese. *Livestock Science* **139**(1–2): 91–99.

Vázquez-Rowe I, Moreira MT, Feijoo G (2011) Life cycle assessment of fresh hake fillets captured by the Galician fleet in the Northern Stock. *Fisheries Research* **110**(1): 128–135.

Vermeir I, Verbeke W (2006. Sustainable food consumption: exploring the consumer "attitude – behavioral intention" gap. *Journal of Agricultural and Environmental Ethics* **19**(2): 169–194.

Wackernagel M, Rees W (1996) *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island, BC: New Society Publishers.

Weidema BP, Thrane M, Christensen P, Schmidt J, Løkke S (2008) Carbon footprint. *Journal of Industrial Ecology* **12**(1): 3–6.

Weidmann T, Minx J (2008) A definition of 'carbon footprint'. In: Pertsova CC (ed) *Ecological Economics Research Trends*. New York: Nova Science Publishers, pp .1–11.

Williams H, Wikström F (2011) Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items. *Journal of Cleaner Production* **19**(1): 43–48.

Yonei Y, Ohinata H, Yoshida R, Shimizu Y, Yokoyama C (1995) Extraction of ginger flavor with liquid or supercritical carbon dioxide. *Journal of Supercritical Fluids* **8**(2): 156–161.

Zufia J, Arana L (2008) Life cycle assessment to eco-design food products: industrial cooked dish case study. *Journal of Cleaner Production* **16**(17): 1915–1921.