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Research Developments in Methods to Reduce the Carbon Footprint of the Food System: A Review

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Global warming is a worldwide issue with its evident impact across a wide range of systems and sectors. It is caused by a number of greenhouse gases (GHGs) emissions, in which food system has made up of a large part. Recently, reduction of GHG emissions has become an urgent issue to be resolved in the food system. Many governments and organizations are making great endeavors to alleviate the adverse effect of this phenomenon. In this review, methods to reduce the carbon footprint within the life cycle of a food system are presented from the technical, consumption behavior and environmental policies perspectives. The whole food system including raw material acquisition, processing, packaging, preservation, transportation, consumption, and disposal are covered. Improving management techniques, and adopting advanced technology and equipment are critical for every stage of a food system. Rational site selection is important to alleviate the influence of land use change. In addition, environmental choices of packaging stage, reduction in refrigeration dependence, and correct waste treatment are essential to reduce the total carbon footprint of the production. However, only technical methods cannot radically reverse the trend of climate change, as consumption behaviors present a great deal of influence over climate change. Appropriate purchase patterns and substitution within food product categories by low carbon products can reduce GHG emissions. Development of methods to calculate the carbon footprint of every kind of food and its processing technology enable people to make environmental choice. Policy can shape and cultivate the new code of consumption and influence the direction of emerging technology and science. From political perspectives, government intervention and carbon offset are common tools, especially for carbon tax and a real or implicit price of carbon. Finally, by mitigating the methodologies described above, the rate and magnitude of climate changes can be also reduced to some extent.

Keywords Carbon footprint, greenhouse gases emission, life cycle assessment, food system, consumption behavior, environmental policies

INTRODUCTION

Global warming is a major issue because the entire environment, even the Earth is dramatically affected by climate change. Climate warming will bring about catastrophic consequences such as extinction of plant and animal species, rising of sea levels and melting of snow and ice, etc. (Bernstein et al., 2008). The main cause of climate warming is the changes in the atmospheric concentrations of GHGs (greenhouse gases) including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), aerosols, land cover, and solar radiation (Bernstein et al., 2008). Normally, GHG emissions are linked to many factors such as agriculture cultivation, food processing, use of fossil fuels, industrial discharge, etc. Table 1 shows the share of food system GHG emissions on total GHG emissions from the published literature, indicating that the food system has taken a large part in GHG emissions. Therefore, the agri-food industry not only needs various processing techniques such as cooling (Hu and Sun, 2000; Wang and Sun 2001), freezing (Delgado et al. 2009), drying (Sun 1999; Sun and Woods 1993, 1994, 1997; Sun and Byrne 1998; Delgado and Sun 2002), and edible coating (Xu et al. 2001) for food quality and safety enhancement, and novel evaluation and detection techniques such as computer vision (Du and Sun, 2004, 2005; Valous et al., 2009) and hyperspectral imaging (Kamruzzaman et al., 2011; 2012;

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Table 1 The share of food system GHG emissions on total GHG emissions from the published literature

References	The share of food system GHG emissions on total emissions
Tukker et al. (2006)	Food and drink, tobacco and narcotics were responsible for 20–30% of the various environmental impacts of total private consumption in the 25 Member States of the EU.
Hertwich and Peters (2009)	The contributions of eight categories i.e. construction, shelter, food, clothing, mobility, manufactured products, services, and trade for GHGs emission were analyzed and the results showed that food was the most important category that accounted for nearly 20% of GHG emissions.
Benders et al. (2012)	368 consumer expenditure items in an average Dutch household were combined into 12 domains and food was in second place, accounted for 19%.
Berners-Lee et al. (2012)	The average population-weighted diet produced a carbon footprint of 7.4 kg CO_2eq person^{-1} day^{-1} or 2.7 t CO_2eq y^{-1}, which represents 27% of direct UK GHG emissions, or 19% of total UK emissions.

ElMasry et al, 2011, 2012; Pu et al., 2014; Liu et al., 2014) for quality and safety assurance and control, but also needs to develop criteria and methods to assess and reduce GHG emissions. However, due to the complexity and heterogeneity of the food system, it is a difficult task to assess the GHG emissions.

As it is known, carbon footprint has been commercialized and has become a useful tool to shape consumers' own climate-friendly behaviors, enhance a company's image, and provide right incentives for governments (Peters, 2010; Pandey et al., 2011; Cellura et al., 2012). Carbon footprint, which is normally expressed in carbon dioxide equivalent, can be defined as exclusive total amount of carbon emissions caused directly and indirectly by an activity or accumulated over the life stages of a product (Wiedmann and Minx, 2007). There are two ways available for calculating the production of carbon footprint: the "bottom-up" way that is based on process analysis (PA) and the "top-down" way that relies on environmental input–output (EIO) analysis. Both methodologies are based on the principle of life cycle assessment (LCA) (Wiedmann and Minx, 2007), which includes consecutive and interlinked stages of a product system, from raw material acquisition to final disposal (ISO, 2006). A simplified diagram of life cycle stages in the food system is expressed in Fig. 1 (Garnett, 2008). The life cycle of a food system consists of an agricultural stage, processing stage, packaging stage, transportation and preservation stage, food consumption, and eventual disposal stage. Due to the low availability of measured data and disunity of assessment in the complex food system, outcomes obtained are usually different. Therefore, it is of great significance to conduct research on carbon footprint of the food system, which can indicate where the inefficiency can be improved.

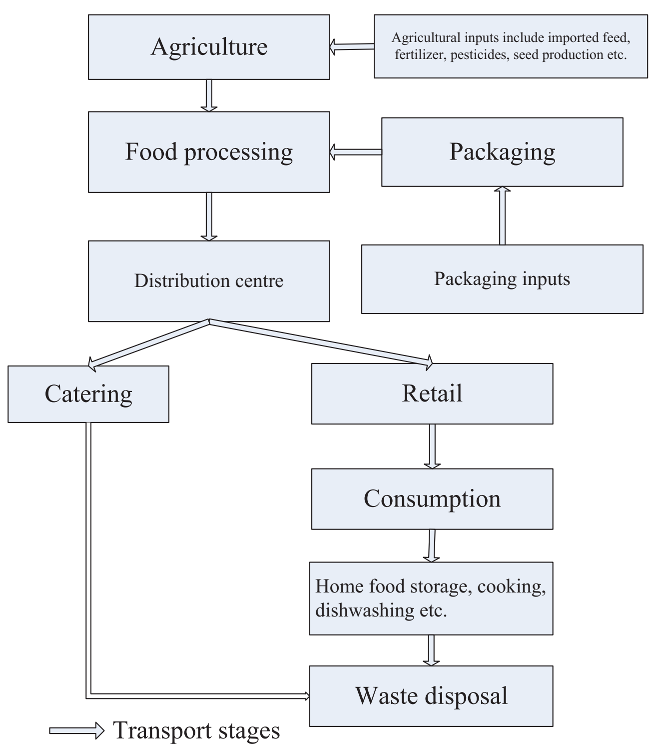

Figure 1. A simplified diagram of life cycle stages in the food supply chain.

Climate change is a social problem, which involves governments, enterprises, and individuals. Facing the increasingly severe environmental situation, it is necessary to reduce the amount of GHG emissions. "Kyoto protocol" in 1997 requested relevant parties to reduce their emissions of greenhouse gases by no less than 5% in the commitment period 2008 to 2012 compared to 1990 level (UNFCCC, 1998). Improving energy efficiency and cutting energy use can directly provide many possibilities to reduce GHG emissions. However, these measures do not radically reduce the inherently GHG-intensive items, because they could not change the demand and supply of the food industry (Garnett, 2008). If consumers respond by seeking substitute goods with lower carbon emissions, then companies responsible for supplying goods with a higher carbon footprint will see a decrease in sales (Edwards-Jones et al., 2009). Meanwhile, environmental policies such as carbon tax or carbon subsidy also play a big role on carbon emissions through changing the direction of technology development (Hémous, 2012). Therefore, it is meaningful to study the environmental methods from the technological, behavioral, and policy perspectives.

Recent studies about carbon footprint within the food system have been focusing on agriculture, consumption and food waste. Little information has been provided on the reduction measures of carbon footprint within the holistic food system.

Table 2 Shares of different stages within the food system from different literatures

Food stages	GHG emission share	References
Raw material acquisition	Agricultural activities were responsible for 6.3% of total U.S. GHG emissions in 2010.	USEPA (2012)
	The agricultural sector produced about 8% of all GHG emissions in Canada.	Gan et al. (2011)
Food processing	Malting and brewing or distilling operation was responsible for 14.21% and 25.51% of the total carbon footprint of beer and spirit, respectively.	Garnett (2007a)
Food packaging	Food packaging constituted the bulk of total packaging waste.	Marsh and Bugusu (2007)
Food transportation and preservation	Food transport accounted for 25% of all heavy goods vehicle kilometers in the UK, which create 19 Mt CO_2	Smith et al. (2005)
	Supermarkets consumed up to 5% of the UK's total energy, 50% of which was used in refrigeration of food.	Davies et al. (2012)
Food consumption	GHG emissions for food in the Italian family were 445 kg CO_2eq per average family, with a main contribution of basic goods (264 kg CO_2eq), packaging (61 kg CO_2eq), and trade (51 kg CO_2eq)	Cerutti et al. (2012)
	For fresh produce, the contribution of the cooking stage is relatively high with respect to GHG emissions.	Garnett (2008)
Disposal stage	Greenhouse gas emissions from postconsumer waste and wastewater contribute about 3% of total global anthropogenic GHG emissions.	Bogner et al. (2008)
	Emission sources of waste management activities generated 1.9% of total U.S. GHG emissions in 2010.	USEPA (2012)

The measures to reduce energy inputs in the US food system were introduced by Pimentel et al. (2008). In addition, Garnett (2008) discussed methods to reduce carbon emissions from the technological, behavioral, and policy perspectives, while Roy et al. (2009b) presented some LCA studies on agricultural and industrial food products; however, both studies failed to give an overview of research development of carbon footprint within the whole-food systems. Recently, Garnett (2011) discussed the possibility of reducing GHG emissions from technological mitigations and behavior changes, however, post-farm gate stages were not systematically studied. Therefore, this review will give detailed discussion about methods to reduce carbon footprint in the food system from the technical perspective based on the principle of LCA as well as the influences of behavioral and environmental policies.

SOURCES OF GHGs WITHIN THE FOOD SYSTEM

GHG emissions from food systems calculated in different studies vary due to differences in methodological approaches, boundary conditions, assumptions, and the quality of the data obtained. Moreover, emission contribution at country-level from the food system is related to other sectors such as transport (Garnett, 2011). The influences of different stages are varied, and so to the sorts of food. The farming stage is the most important source of impacts. Enteric fermentation and manure management produced 21.2% and 7.8% of total CH_4 emissions from anthropogenic activities, respectively (USEPA, 2012). Agricultural soil management activities such as fertilizer application and other cropping practices are the largest source of N_2O (USEPA, 2012). Despite very extensive internet searches, very few studies about the shares of energy use and CO_2 emissions resulting from food processing have been found. However, the share of food processing can be considerable when foods are subject to major processing for example from tomatoes to ketchup (Foster et al., 2006). Similarly, for some foods such as bottled drinks, the packaging stage is significant (Foster et al., 2006). On the other hand, different life stages are linked together by transportation, and in most cases, transportation consumes more energy than cultivation in the life cycle of fresh produce such as apples (Jones, 2002). There is a special agreement to guide the transportation of perishable foodstuffs and on the special equipment to be used for such carriage (ITCECE, 2010). In addition, for fresh produce, the cooking stage merits attention, the contribution of which is relatively high with respect to GHG emissions (Garnett, 2008). Table 2 summarizes shares of different stages within the food system.

REDUCING FOOD CHAIN GHG EMISSIONS

In the food system, the rate and magnitude of climate changes can be reduced by many mitigation methodologies (Bernstein et al., 2008). In the following, these methodologies will be elaborated from technical, behavioral, and political perspectives.

Technological Perspectives

Raw Materials Acquisition

There are many mitigation technologies in agriculture. By 2030, the global agricultural mitigation potential may reach 5500-6000 Mt CO_2eq/yr excluding fossil fuel offsets from biomass (Smith et al., 2008). This part will focus on two kinds of reduction measures, i.e. improved cultivation technology and land use change.

Improved Cultivation or Breeding Techniques

There are many mitigation technologies that can be used to reduce GHG emissions in agriculture, including improving rice cultivation techniques and livestock and manure management to reduce CH_4 emissions, improving nitrogen fertilizer application techniques to reduce N_2O emissions, and improving energy efficiency and crop yields (Bernstein et al., 2008). For example, comparing the green bean cropping in a screenhouse with or without a misting system and in an open-field, results showed that the open-field treatment had the greatest environmental impact due to its lower yields (Romero-Gámez et al., 2012). Direct energy use in agriculture results in large amounts of GHG emissions. Temperature integration regimes, which include taking into account outside weather conditions, a greater use of thermal screens, making greater use of correctly sized, insulated thermal stores, and an increased uptake of CHP (combined heat and power) technology, can save energy use for heating. By using mitigation technologies, in the United Kingdom, it was predicted that the overall potential energy efficiency saving would be around 3000 GWh by 2015, consequently, this would reduce carbon emissions by about 175,000 tons per annum (Warwick and Park, 2007).

Diversified cropping systems are the promising strategies in mitigating GHG emissions from farming. By comparing to cereal-based monoculture systems, Gan et al. (2011) showed that diversified cropping systems where oilseed, pulse, and cereal crops were arranged in well-defined cropping sequences could lower the carbon footprint of durum wheat by 22%. Hergoualc'h et al. (2012) also found that converting a coffee monoculture to a coffee agro-forestry plantation system could produce a net GHG absorption rate about four times larger than in the monoculture system. In addition, conservation tillage management is another effective way to reduce GHG emissions but its effect needs to be further studied (Zentner et al., 2004; Maraseni and Cockfield, 2011). Attention should also be paid to the appropriate application of fertilizers, as over 40% of the carbon footprint at the farm stage comes from N_2O emissions owning to the application of N fertilizers (Ingwersen, 2012). On the other hand, a large amount of operational energy is in relation to water harvesting and irrigation (Mrini et al., 2001; Chen et al., 2009), consequently, positive mitigative effects can be achieved by improving irrigation and drainage management (Smith et al., 2008). Griffiths-Sattenspiel and Wilson (2009) and Mrini et al. (2001) showed that various types of irrigation systems such as flood, sprinkler, drip, micro-irrigation and other new water-saving technologies had different environmental impacts. GHG reduction can be achieved by substitution of older inefficient and energy-intensive systems (Jones et al., 2012; Maraseni et al., 2012a, 2012b; Mushtaq et al., 2013). In addition, well water supplies need large energy, as Wang et al. (2012) showed that GHG emissions from groundwater pumping for irrigation in China was 33.1 $MtCO_2$eq, around 0.58% of national total emissions, therefore, an overall reduction in GHG emissions can be gained by using surface water supplies (Maraseni et al., 2009). Moreover, Maraseni et al. (2010) demonstrated that although water reuse contributed significantly to water productivity, priority should be given only in areas where water scarcity is a serious issue due to the use of additional energy. Furthermore, water conservation, water harvesting, and water-efficient farming systems can enhance soil carbon sequestration in dryland and improve agronomic yields (Lal, 2004).

The livestock sector accounts for about a fifth of the anthropogenic GHG emissions (Gerber et al., 2010). Improved breeding methods can be applied to reduce GHG emissions, as Philippe et al. (2012) showed that the effects of fattening pigs kept on the straw flow system reduced N_2O by 55%, CH_4 by 46%, and CO_2 by 10%, as compared with those kept on straw-based deep litter. Dietary manipulation is also helpful for CH_4 abatement, a 38% reduction in enteric methane emissions for grain-finished beef was discovered by Peters et al. (2010). Moreover, improved fans, ventilation control, ducting design and cleaning, adoption of high-efficiency lighting, and lighting layouts can also be used to save large amount of electricity in the poultry and pigs sectors (Warwick and Park, 2007).

Land Use Change

Land uses cause large amounts of GHG emissions (Ponsioen and Blonk, 2012). Effects of land use changes must be included into the carbon footprint standards to avoid underestimation of carbon footprint of production, as Hermansen and Nguyen (2012) showed that pig meat produced from two pig systems without land use impacts had a slightly lower GHG emissions of 3.5 and 3.2 kg CO_2eq/kg, however, by taking into account the potential land use change related to soy meal production, the total estimated GHG emissions per kg pork produced increased considerably to 7.1 and 5.7 kg CO_2eq, respectively.

Rational site selection is important to alleviate the influence of land use change. Two major aspects of land uses in relation to livestock production are occupation of land for feed production and that for livestock production (Hermansen and Nguyen, 2012). Cederberg et al. (2011) estimated the emissions from the conversion of forest to pasture in the Legal Amazon Region of Brazil, and showed that the carbon footprint of beef produced on newly deforested land was more than 700 kg CO_2eq/kg carcass weight if direct land use emissions were annualized over 20 years. Furthermore, converting a primary forest to a pineapple farm was also a bad alternative, which resulted in a tenfold increase in a carbon footprint (Ingwersen, 2012).

Food Processing

Food processing is an important stage within the food system. Food processing industry is one of the largest industrial sectors and it is connected to other sectors such as power plants and metal manufacturing. If other sectors reduce their own carbon emissions, the final production carbon footprint will decline correspondingly. Key mitigation technologies in the industrial sectors include more efficient end-use electrical equipment, heat and power recovery, material recycling and substitution, control of non-CO_2 emissions, combustion of carbon neutral biomass-based fuels, and a wide array of process-specific technologies, advanced energy efficiency, capture and sequestration of CO_2, etc. (Bernstein et al., 2008; Pękala et al., 2010). The following technologies including capture and sequestration of CO_2, process control and optimization, computational fluid dynamics, cutting use of fossil fuels, and technical improvement will be discussed.

Capture and Sequestration of CO_2

Capture and sequestration of CO_2 from fossil fuel power plants are the potential methods to control GHG emissions, although with many disadvantages such as major capital costs as well as reduction of thermal efficiency and power output (Rao and Rubin, 2002; Tan et al., 2009). There are many capture and sequestration measures such as absorption, adsorption, membrane separation, chemical-looping combustion, hydrate-based separation, forestation, ocean fertilization, mineral carbonation techniques, underground injection, and direct ocean dump (Yang et al., 2008; Kwon et al., 2011). Zhou et al. (2010) developed a knowledge-based expert system with artificial intelligence techniques to help the operator monitor the operating conditions of the CO_2 capture pilot plant in real time and to enhance the plant performance and CO_2 capture efficiency.

Carbon capture and utilization (CCU) is a new method for chemical exploitation of CO_2. The intensified chemical or physical utilization of CO_2 by CCU offers an important option for the total strategy of carbon management and more efficient chemical processes with reduced CO_2 footprint (Markewitz et al., 2012).

Process Control and Optimization

At the processing level, process control and optimization is helpful to ensure that production operations are the most efficient (Masanet et al., 2008). It is also essential to make a strong, corporate-wide management program for saving-energy in the food industry (Galitsky et al., 2005). Moreover, industrial symbiosis offers an opportunity to reduce their host ecological impact (Boons et al., 2011).

Process intensification (PI) is an engineering development that leads to a substantially smaller, cleaner, safer, and more energy-efficient technology. PI has many applications such as drying, crystallization, emulsification, and mixing for carbon reductions in the food system (Reay, 2008).

Process integration should be one part of energy management program. Taking heat integration as an example, process integration means combining several processes to reduce resources consumption and harmful emissions to the environment (Friedler, 2010). There are multiple heating and cooling streams, which can be linked in a thermodynamically optimal manner in the fruit- and vegetable-processing industries (Masanet et al., 2008), while Ahmad et al. (2011) illustrated that the heat integration analysis could gain savings of approximately 72% in hot utilities and 88% in cold utilities on biomass gasification plant for hydrogen production. Recently, pinch analysis procedure is frequently used for energy planning and for allocation of different energy resources among different energy demands within carbon emission limits (Tan and Foo, 2007; Lee et al., 2009; Wan Alwi et al., 2012). With pinch analysis on the mechanical vapor recompression technology, the heat demand and emission could be reduced by 15.7 and 22.6%, respectively, compared to a three-effect vacuum evaporator system (Tuan et al., 2012). The heat exchanger networks of by-product recovery subsystem from glyphosate production could also be optimized by the principle of pinch technology (Yuan et al., 2012). In addition, water management program and advanced technology can be used to reduce the carbon footprint of water in a food company such as a winery factory (Galitsky et al., 2005), as Griffiths-Sattenspiel and Wilson (2009) showed that water conservation, efficiency, reuse, and low impact development strategies could be used to reduce energy consumption and GHG emissions, while Lim and Park (2008) illustrated that the cooperative water network system could reduce the carbon footprint by 6.3% compared to the individual water network system.

Computational Fluid Dynamics Technology

Computational fluid dynamics (CFD) is a simulation tool, which uses powerful computer and applied mathematics to model fluid flow situations for the prediction of heat, mass and momentum transfer, and optimal design in industrial processes (Xia and Sun, 2002). CFD is an effective and efficient design and analysis tool for the food industry, and has been used in ventilation, drying, sterilization, refrigeration, cold display and storage, and mixing processing (Ambaw, Verboven, Delele, Defraeye, Tijskens, Schenk, et al., 2012; Bernard, Broyart, Absi, Granda, & Relkin, 2012; Delele, Ngcobo, Opara, & Meyer, 2012; Norton and Sun, 2006; Ould Ahmedou, Rouaud, & Havet, 2008; Padmavati & Anandharamakrishnan, 2012).

Conduction, natural convection, and forced convection are important means for the heating process. The knowledge of the mechanism of the heating process is crucial to save energy. Numerical modeling technology offers an efficient and powerful tool to simulate the heating and cooling processes of the food industry (Abdul Ghani et al., 1999). Ousegui et al. (2012) developed an optimal control method based on CFD simulation for the optimization of heat flux during a baking process. Abdul Ghani and Farid (2007) used CFD to simulate the high pressure processing, and predicted temperature distribution, velocity, and pressure profiles of liquid food (water) and solid–liquid food mixture, while Lespinard and Mascheroni (2012) used CFD to model the natural convection heating of liquid food packed in glass jars of different sizes and volumes during sterilization.

Another utilization of CFD is to optimize design of cooling or refrigeration management. Optimization during cooling process of orange juice was conducted after high temperature short-time sterilization (Wang et al., 2011). A novel forced-air cooling system capable of promoting rapid, uniform, and energy-efficient cooling of packed strawberries was also developed (Ferrua and Singh, 2011). In addition, the effect of cooling on microbial safety of shell eggs was evaluated by CFD model (Kumar et al., 2012).

Cutting Use of Fossil Fuels

For reduction of GHG emissions, the current fossil fuel systems should be changed gradually to clean and reliable energy systems (Dagdougui, 2012). Sunlight is known as a renewable source. Solar energy can be used in defrosting, cleaning, pasteurizing, sterilizing, cooking, and drying processes of food system (Schnitzer et al., 2007). Thus sunlight has been used as a power output by Pazheri et al. (2012) to decrease emissions by reducing the bagasse moisture content. Sunlight can also be utilized by photovoltaic panels to convert it into electricity. Masanet et al. (2008) showed that a 114 kW photovoltaic power system in one food processing plant could avoid about 2500 tons of CO_2 emissions.

Bio-fuel is considered to be environmentally friendly and can serve as a suitable replacement of the conventional products from fossil/nonrenewable resources (Chiellini and Morelli, 2011). In evaluating effects of bio-fuel replacement, ecosystem carbon payback time (ECPT) is normally used, which is defined as the number of years required for avoiding fossil fuel emissions from bio-fuels to compensate for losses in ecosystem carbon stocks during land conversion. ECPT of different bio-fuels showed that the expansion of bio-fuels into degraded or already cultivated land could provide almost immediate carbon savings, however, meaningful carbon benefit would not be foreseeable if bio-fuels were expanded into tropical forests (Gibbs et al., 2008). Therefore, degraded or already cultivated land could be used to produce biomass material. To avoid the potential pitfalls of traditional bio-fuel crops, a variety of alternative bio-fuel feedstock are currently being studied. *Camelina sativa* (L.) as a promising crop for biodiesel production can reduce GHG emissions and fossil fuel use by 40–60% when compared to petroleum diesel (Krohn and Fripp, 2012). Microalgae are also proved to be a potential source of biodiesel (Hwang et al., 2009).

Cutting use of fossil fuels can also be achieved by reuse energy contained in the waste and heat recovery, as landfill gas can be used to produce pipeline-quality gas and electricity (Zietsman et al., 2008), while heat recovery is an energy-efficiency measure for blanching, drying and dehydrating, evaporation and concentration, frying, pasteurization and sterilization, and peeling for the fruit- and vegetable-processing industries (Masanet et al., 2008). In addition, agriculture refuses can be used for producing energy. Escobar et al. (2009) illustrated that the biological conversion of ligno-cellulosic residues to cellulosic ethanol, methanol, DME, and bio-hydrogen was useful for reduction of GHG emissions. Furthermore, a power plant using de-oiled pomace and waste wood was compared with that using coal, with the former showing important environmental advantages in terms of GHG emissions (Intini et al., 2012).

Technical Improvement

At the component and equipment level, steam, motor, pump, refrigeration, and compressed air systems are universal for the food industry. Regular preventative maintenance, proper loading and operation, and replacement of older equipment with higher-efficiency models can be used to lower energy consumption of universal systems (Masanet et al., 2008). Choosing appropriate equipment size can also reduce energy losses (Galitsky et al., 2003), for example, Jaber (2002) estimated that in the Jordanian industries replacement of over-sized or inefficient motor-driven systems could avoid 80 kt of CO_2 emissions from 2003 to 2010. Lung et al. (2006) also estimated that in the United States, converting standard steam and hot water blanchers to energy-efficient blanching systems could avoid CO_2 emissions by 29-64 kt CO_2 in the food-processing industry in 2020. As conventional domestic burner (CB) has low thermal efficiency, Jugjai and Rungsimuntuchart (2002) developed the concept of a novel semiconfined porous-radiant recirculated burner (PRRB) for energy savings in the small-scale food-processing industry, and showed that the combination of swirling central flow burner technology with PRRB had a thermal efficiency about twice as high as that of the CB. On the other hand, membrane separation has some advantages over evaporation or distillation due to no heat requirement or phase change (Galitsky et al., 2003).

Owing to the improvement of energy efficiency of processes or reduction of the use of nonrenewable resources, many emerging technologies present environmental benefits (Pereira and Vicente, 2010). Microwave, infrared radiation and vacuum drying have energy efficiency higher than hot air drying (Arikan et al., 2011; Calín-Sanchez et al., 2013a; Calín-Sanchez et al., 2013b). For example, Wang and Sheng (2006) showed that the whole-drying energy consumption of peach decreased with increasing in microwave drying power and infrared drying power, while Gunasekaran (1999) illustrated that combination of pulsing and vacuum drying could substantially improve energy use efficiency. In addition, autoclave pasteurization, high-hydrostatic pressure and modified atmosphere packaging can reduce energy demand and CO_2 emissions compared to conventional pasteurization (Pardo and Zufia, 2012). Furthermore, pulsed electric fields (PEF) can also be used to reduce carbon emission, as Vorobiev and Lebovka (2010) showed that for the production of damaged plant tissues, PEF method could use less energy than other techniques such as mechanical, enzymatic, heating, or freezing/thawing, while Lung et al. (2006) estimated that in the United States by converting continuous heat exchangers to PEF pasteurization in not-from concentrate orange juice manufacturing, potential emissions reduction would be about 35-66 kt CO_2 in 2020. Besides, Töpfl (2006) illustrated the combination of heat and PEF treatment could cut energy consumption.

Cutting the use of energy can also be realized by self-generation electricity facilities. Self generation such as co-generation, tri-generation, or renewable energy systems can be used to reduce the energy consumption of utilities services (Masanet et al., 2008), for example, about 21% of electricity in a corn wet milling plants was co-generated onsite (Galitsky et al., 2003). In addition, Galitsky et al. (2005) showed that electricity facilities such as efficient transformers and power factor correction systems could be used to reduce energy loss.

Food Packaging

Food packaging is important which makes food travel safely for long distances from their point of origin to consumption, however, it causes serious environmental issues. Thus social and environmental consciousness in relation to food packaging should be taken into consideration (Marsh and Bugusu, 2007).

Impacts of packaging on the environment depend on the packing materials. Humbert et al. (2009) compared plastic pot and glass jar used for baby food products, and showed the plastic pot system reduced the carbon footprint by 28%–31% than the glass jar system, while Poovarodom et al. (2012) showed that the retort cup system for tuna products could reduce the overall GHG emissions by 10% and 22% by comparing to metal can and retort pouch systems, respectively. Moreover, environmental performances of alternative packaging systems for retail sales of coffee were also evaluated, and it was showed that the use of polylaminate bags was an alternative to metallic cans, even though this solution did not favor material recycling (De Monte et al., 2005).

Size is another factor that influences the carbon footprint of food packaging. Point (2008) showed that a 30% reduction in bottle weight for wine production resulted in reductions between 4%–23% of the total life cycle emissions, besides Ingwersen (2012) illustrated that the carbon footprint of packing boxes decreased by abandoning the crown owing to the increase of numbers of fresh pineapples per box. Moreover, De Monte et al. (2005) carried out comparison among various packing systems such as cans with a capacity of 3 kg, 250 g, and 125 g, and the results showed that bigger packaging alternative had a smaller impact with respect to the functional unit of 1 kg of packed coffee. On the other hand, packaging design and material recycling can also reduce the impact on environment. Pimentel et al. (2008) elucidated that multiple layers for cereals should be replaced by single and more durable package, while Hospido et al. (2006) indicated that an increase in the percentage of the recycled material could reduce environmental impact of canned-tuna product.

Food Transportation

Food transportation is a linked stage during the food life cycle, which in most cases consumes more energy than cultivation in the life cycle of fresh produce such as apples (Jones, 2002). The food transport accounts for 25% of all heavy goods vehicle kilometers in the United Kingdom, which creates 19 Mt CO_2 (Smith et al., 2005). There are various mitigation technologies in the distribution stage, such as more fuel-efficient vehicles, hybrid vehicles, cleaner diesel vehicles, land-use and transport planning, appropriate suppliers and transportation mode, second-generation bio-fuels, and higher efficiency aircraft (Bernstein et al., 2008; Cholette and Venkat, 2009; Benjaafar et al., 2010). In addition, means/end analysis can be used to identify a more environmental option for food transportation (Jones, 2002).

Reducing the transportation distance and increasing the stored and traded quantities can make local food systems more sustainable (Van Hauwermeiren et al., 2007), as Point (2008) showed that an increase of consumer transport from 5 to 25 km round-trip driving distance resulted in an increase of GHG by 120.51%. However, it is not always effective to promote local production. In evaluating effects of transport distance, the term of food mile is normally used, which is defined as the distance of food travelled from where it is grown or raised to where it is ultimately purchased by consumers or end-users (Pirog et al., 2001). Field-grown lettuces from Spanish into the United Kingdom produce less GHG emissions than those plant in the UK-protected systems during winter because the latter needs larger energy to heat the glasshouses (Hospido et al., 2009). Recently, roof top greenhouses (RTGs) systems have emerged to meet the demands of reducing transportation distances between cities, which include the roof tops of buildings and protected crops using intensive hydroponic culture, and Sanye-Mengual et al. (2012) showed that the change from the current situation to RTGs systems could reduce 441 g CO_2eq/kg tomatoes in Barcelona. In addition, more environmental friendly transportation can generate less carbon emissions (Hoen et al., 2010), as Beccali et al. (2010) indicated that using railways could improve environmental performance of citrus products.

Food Preservation

Today's food system is built upon refrigeration which is a feature of almost every stage in the supply chain for many foods (Garnett, 2007b), as refrigeration during transport contributes 15% of the total carbon footprint of fresh pineapple, while storage contributes 5% of the total carbon footprint (Ingwersen, 2012). Thus minimizing storage time is a simple and useful measure to reduce carbon emissions (Van Hauwermeiren et al., 2007).

Advanced technologies can diminish the negative influence of food preservation on environment. Bahman et al. (2012) showed that a 5% reduction in storage with relative humidity control could reduce refrigeration load by 9.25% of the display case, consequently, resulted in a 4.84% reduction of total store energy load. Tassou et al. (2009) also showed that in the transport refrigeration system, thermally driven refrigeration technologies were environmental alternatives to the conventional mechanical compressor based on the common vapor compression cycle. In addition, during transportation and refrigerated storage, radio frequency identification device (RFID) technology can be used for temperature tracking to correctly adjust and control the refrigeration unit, thus saving energy during refrigeration (Amador et al., 2009). Moreover, Davies et al. (2012) also illustrated that low emissivity materials applied in food packaging could improve refrigeration system efficiency. Furthermore, Dempsey and Bansal (2012) indicated that by employing variable speed drives on fans, air blast freezing had great potential to save energy.

Renewable resource has great potential to diminish GHG emissions. Solar energy can be used for food preservation. VijayaVenkataRaman et al. (2012) developed a solar crop drying system that combined fuel burning with the energy of the sun, and showed that it could reduce fossil fuel consumption.

Food Consumption

The carbon footprints of many food productions are mainly related to energy use for cooking (Edwards-Jones et al., 2009). Due to the influence of habits, the stage of food consumption is very complex. This part mainly introduces methods through improving cooking technology and equipment.

Improving cooking technology and equipment is useful to mitigate climate change. Improving cook stove is an alternative (Whitman et al., 2011), as Bhattacharya and Abdul Salam (2002) showed that about 110 g CO_2eq was released by traditional wood-fired stoves delivering 1 MJ of useful energy to the cooking pot, in case of improved wood and biogas, the CO_2eq released were 42 and 5 g, respectively, while Das et al. (2006) evaluated the energy used during normal and controlled cooking of both un-soaked and presoaked rice by an electric rice cooker and a pressure cooker, and showed that electric rice cooker was the most energy-efficient, however, controlled energy input, under pressure and with presoaking were beneficial to energy-saving. On the other hand, there are some eco-friendly cooking tips such as minimizing use of oven, putting lids on saucepans, no use of the oven for individual portions and so forth (Garnett, 2008), while Roy et al. (2009a) showed that the larger the amount of rice in a batch was cooked, the lower the energy consumption per unit of rice during cooking was.

Waste Treatment

The amount of household wastes produced globally is significant. For example, UK households waste 6.7 Mt of food every year, roughly one-third of food purchased, and most of this food waste goes to landfill, which is liable to create methane (Ventour, 2008). Current mitigation technologies include recycling and waste minimization; landfill gas recovery; improved landfill practices; waste incineration with energy recovery; engineered wastewater management; controlled composting, incineration, anaerobic digestion, thermal treatment; expanded sanitation coverage, and bio-filter to optimize CH_4 oxidation (Bernstein et al., 2008; Bernstad and la Cour Jansen, 2012a; Matsuda et al., 2012). The overall stages of waste disposal consist of separate discharge, collection, transportation, treatment, and final disposal (Kim and Kim, 2010). In the following, waste treatment is described in three stages, i.e. pretreatment of food waste, recycle and reuse, and other waste treatments.

Pretreatment

Pretreatment includes separate discharge, collection, and transportation. Improved pretreatment processes can increase the overall environmental benefits (Bernstad et al., 2012), as Bernstad and la Cour Jansen (2012b) showed that four separate collections of household food waste in paper bags for decentralized drying before collection resulted in a larger net avoidance of global warming, while Matsuda et al. (2012) illustrated that incineration scenario, separate collection and anaerobic digestion scenario (SepBio), and mechanical sorting and anaerobic digestion scenario (MecBio) resulted in the GHG emissions of 123.3, 118.6, and 119.5 kt CO_2eq/year, respectively. Moreover, prevention of food losses enhanced by separate collection can largely reduce GHG emissions, as Matsuda et al. (2012) showed that avoiding edible food loss and draining moisture reduced the GHG emissions by 17.1 and 0.5 kt CO_2eq/year, respectively.

Recycle and Reuse

Recycling is an effective method to reduce GHG emissions (Chen and Lin, 2008), as different food waste disposal options including dry feeding, wet feeding, composting, and landfill produced 200, 61, 123, and 1010 kg CO_2eq, respectively (Kim and Kim, 2010). For food industries, Japan established a food recycling law (Promotion of Utilization of Recyclable Food Waste Act) in 2001, to reduce food waste and to promote recycling (Takata et al., 2012). Ogino et al. (2012) carried out four treatments of rice-washing water including centrifugation, heating evaporation, dehydration, and discharge, and showed that liquid feed production by centrifugation had a remarkable reduction in environmental impact compared with discharge. Furthermore, energy from landfill gas, incineration, composting, and anaerobic digester biogas generates an indirect reduction of GHG emissions, because of the conservation of raw materials, improved energy and resource efficiency, and fossil fuel avoidance (Bogner et al., 2008; Bernstad and la Cour Jansen, 2011), while the resulting humus from composting can be used as a natural fertilizer to replace chemical fertilizers (Marsh and Bugusu, 2007; Okareh et al., 2012). On the other hand, the reuse of materials may be helpful to reduce the environmental load, as Muthu et al. (2011) showed that a higher percentage of reuse can significantly scale down the carbon footprint of various types of shopping bags.

Other Treatments

Different waste treatment methods produce different amounts of GHG emissions (Poulsen and Hansen, 2009). Recently, direct landfill of raw food wastes has been banned in Korea (Kim and Kim, 2010). Khoo et al. (2010) studied three treatment methods including incineration, recycling via anaerobic digestion combined with composting of digestive matter, and a proposed small-scale aerobic composting, and showed that anaerobic digestion recycling process was the most beneficial, followed by aerobic composting and incineration of food waste. Foolmaun and Ramjeeawon (2012) also evaluated five sorts of waste management scenarios for used PET bottles including 100% landfill, 100% incineration with energy recovery, 50% incineration and 50% landfill, 34% flake production and 66% landfill, and 100% flake production, and concluded that the highest and least environmental impacts were 100% landfill and incinerated with energy recovery. In addition, hydrothermal carbonization (HTC) is a more beneficial method than traditional, dry thermo-chemical conversion processes for solid waste treatment (Berge et al., 2011; Hwang et al., 2012; Lu et al., 2012). Moreover, the conversion of organic waste into fertilizers through earthworm composting offers an alternative to improve productivity without environment pollution (Zandonadi and Busato, 2012).

Consumption Behavior

The global warming potential of different food groups is diverse, as Nemecek et al. (2012) investigated 27 crops, and showed that the global warming potential values per kg of fresh mass were the lowest for sugar crops, followed by root crops, vegetables and fruits, and oil palm. In addition, typical patterns of diets for the last 50 years proved that food consumption had changed from lower calories diets to higher calories diets that associated with higher GHG emissions (Pradhan et al., 2012). While Benders et al. (2012) divided 111 food items in an average Dutch household into 11 subdomains, and showed that the top three were meat, dairy, and bread, accounting for 25.1%, 24.9%, and 14.8% of the total GHG impact, respectively. According to Garnett (2008), technical methods did not radically reduce the inherently GHG-intensive items, because they could not change the demand and supply of the food industry. Therefore, consumption behavior can play a big role to lower food-related carbon footprints of an average household (Weber and Matthews, 2008; Davis et al., 2010; González et al., 2011). In the following, the effects of dietary shift and appropriate purchase patterns will be discussed.

Dietary Shift

Substitution within food product categories can reduce GHG emissions, such as the substitution of glasshouse products by food products grown in open ground or the substitution of meat by other protein-containing food products such as eggs, nuts, and pulses (Kramer et al., 1999). Roy et al. (2012) studied the life cycle of various types of meat in Japan, and illustrated that a change in consumption patterns from beef to chicken or pork and adoption of a healthy and balanced diet could decrease about 2.5–54.0 Mt CO_2eq, while Saarinen et al. (2012) investigated complete lunches that included home-made portions, ready-to-eat portions and school lunches, and indicated that the protein source of main dish and the type of salad had influence on the climate change. In addition, Roy et al. (2009a) elucidated that a change in rice consumption patterns from well-milled, brown, germinated brown, and parboiled rice to partially-milled could reduce 2–16% of CO_2 emissions. Moreover, decreasing the supplied amount of bottled water has environmental advantages (Friedrich et al., 2009), as Botto et al. (2011) compared tap water and PET-bottled natural mineral water in Italy, and showed that a PET-bottled water consumer (2L per day) who turned into tap water could reduce 163.50 kg CO_2eq/year. Therefore reducing food consumption that uses more energy is an option. Carbon labeling is a good tool, which can tell consumers the environmental impacts about purchasing different products within a substitutable range (Tan et al., 2012). On the other hand, environmental dietary action can result in more changes in the existing production methods in farming, food processing, and distribution (Wallén et al., 2004).

Appropriate Purchase Patterns

Individual effort is significant to minimize the carbon footprint, as consumer can scale down the carbon footprint of various types of shopping bags significantly by a higher percentage of reuse (Muthu et al., 2011). A change in shopping patterns can reduce the environmental load (Roy et al., 2012), as Sanyé et al. (2012) evaluated the environmental impacts of a standard shopping basket purchase in municipal markets of five city centers and a hypermarket in a suburban retail park, and showed that the overall environmental impact associated with a standard shopping basket was 10 times higher on average in a hypermarket than in a municipal market.

Political Perspective

Environmental policies can play a big role in reducing GHG emissions. It is important to raise public environmental awareness (United Nations, 1992). Sundblad et al. (2012) showed that with an increase of participants' environmental awareness, there is an increase in intentions to change personal activities for decreasing carbon emissions. During this process, environmental policies have unparalleled advantages. In addition, environmental policy can change the direction of technological development and the influence of technology changes on global warming, as Hémous (2012) showed that direct technical change accelerated environmental degradation under laissez-faire, but it had positive effects when the appropriate policy was undertaken. Recently, many policies or agreements were established. A key difficulty to set up an international environmental agreement is to design mechanisms that prevent defection without deterring participation (Von Stein, 2008), as Lau et al., (2012) showed that for many environmental policies such as the Kyoto Protocol (UNFCCC, 1998), completely commitment to the effective and collective efforts of global warming mitigation was urgent. Carbon label is also an useful policy instrument, with its main environmental benefits depending on influential change within the supply chain and manufacturer's positive reaction (Tzilivakis et al., 2011); however, it may be hard to deliver GHG reductions over a longer period (Edwards-Jones et al., 2009).

From political perspectives, government intervention and carbon offset are common tools in terms of climate change. In the following, these two methods will be discussed.

Government Intervention

Government intervention such as direct government intervention, mandatory controls, and complete phase-outs can respond quickly to environmental problems (Sovacool, 2010), as Carraro et al. (2012) showed that climate policies normally govern energy saving first and then reduction of the carbon intensity of energy supply. While Taiwan passed the Frameworks of Sustainable Energy Policy aimed to cut off 50% of CO_2 emissions that were based on the 2000 level by 2050 (Hwang, 2011). In addition, Hoen et al. (2010) assessed the effect of emission regulations on the transport mode selection problem, and showed that implementation of a constraint on freight transport emissions could largely reduce the carbon emissions.

For the measures of government intervention, carbon tax provides a simple mechanism to reduce carbon emissions (Benjaafar et al., 2010), which reduce emissions through three approaches, i.e., improving energy efficiency, de-carbonizing the fuel source, and reducing demand for energy (Garnett, 2008). The German government introduced the eco-tax to protect their environment, which promotes conservation, energy efficiency, and the use of renewable energies (Blesl et al., 2007). Furthermore, if a carbon tax system rewards net absorption of CO_2 from the atmosphere, it can incentivize the development of negative emission technologies (Carraro et al., 2012). In addition, Hyder (2008) showed that an international emission-based tax could generate revenue for investment in research and development and subsidies for low-carbon energy and energy efficiency technology, renewable energy, nuclear fusion, carbon capture, and storage technology, reducing deforestation and so on, while Hémous (2012) indicated that without direct incentives to clean research, clean technologies in the polluting industries were difficult to develop in the environmental intervening countries due to the shift of these polluting industries to the environmental no-intervening countries.

Carbon Offset

Carbon offset is an action to reduce GHG emissions that purchasers of a carbon offset compensate for their own emissions by paying someone else (Kollmuss et al., 2008). There are many carbon offset standards such as Clean Development Mechanism (CDM), Gold Standard (GS), Voluntary Carbon Standard 2007 (VCS 2007), VER+, The Voluntary Offset Standard (VOS), Chicago Climate Exchange (CCX), The Climate, Community and Biodiversity Standards (CCBS), Plan Vivo System, ISO 14064-2, and GHG Protocol for Project Accounting (Kollmuss et al., 2008).

The CDM is one kind of emerging carbon market, which aims to realize both sustainable developments in developing countries and cost-effective GHG reductions in developed countries (Olsen, 2007). Sutter and Parreño (2007) assessed 16 officially registered CDM projects, and showed that 72% of the total portfolio's expected certified emission reductions (CERs) may represent measurable emission reductions. Djanibekov et al. (2012) also showed that the CDM forestation programs supporting tree plantations on marginal croplands could enhance sustainable development. In addition, Duic (2003) indicated that CDM induced transfer of clean energy technologies.

A real or implicit price of carbon could create incentives to significantly invest in low-GHG products, technologies and processes, as Bernstein et al. (2008) indicated that global carbon prices rising to US\$ 20–80 / t CO_2eq by 2030 could stabilize GHG concentration at around 550 ppm CO_2eq by 2100. Hua et al. (2011) also investigated the inventory management of the carbon footprint under the carbon emission trading mechanism in firms, and showed that carbon cap and carbon price had a great impact on the retailer's order decisions. However, the implementation of carbon trading has its own issues, such as employee retention issues in carbon trading companies and potential fraud in the offset market in Europe (Environmental Leader, 2009).

DISCUSSION

The goal of enterprise is to make profit, thus it is not reliable to rely on enterprises to decrease their own carbon emissions, as Lung et al. (2006) showed that although some emerging technologies could reduce GHG emissions, they were not necessarily attractive to the industry due to high cost. The increase of people environmental consciousness can compel enterprise to reduce the carbon emission of their production. Tan et al. (2012) showed that if carbon labeling was to be implemented, 68% of respondents would buy certified-green products by looking at the green or energy label. Therefore, it is vital to standardize the guidance which is used to simplify communication such as carbon labeling (Jungbluth et al., 2012). The European Food Sustainable Consumption and Production (SCP) Round Table is perfecting an environmental assessment of food and drink products (Camillis et al., 2012). A few prestigious institutions have also made efforts for standardization formation (Iribarren et al., 2010). Specification for the assessment of life cycle greenhouse gas emissions of goods and services is the first attempt to provide integrated, consistent approaches to calculate the production of carbon footprint (Sinden, 2009). Moreover, Bocken et al. (2012) used a pain/gain tool to compare the benefit of potential GHG emission reduction for a range of options against the implementation difficulties.

Although a growing number of articles on reduction of carbon footprint are published, there is no research to define what low carbon products are. Therefore, development of regulations about definition of low carbon products and their production processes are significant. The establishment of carbon emission measurements and classification standard for each kind of food and its processing technology could significantly reduce carbon emissions of the food chain. Due to a wide range of items and diverse production processes, it may be a breakthrough to establish the food standard from unit operations such as heating process, frozen process, and concentration process. During this process, it is difficult to gain available and enough detail information, due to close similarities between the nature and scale of environmental impact for groups of primary foodstuffs which have considerable similar production conditions (Foster et al., 2006), the results of similar studies can be used to fill the data gap. In addition, some professional tools such as SimaPro (ESU-services Ltd., Zürich, Switzerland), Ecoinvent (The Ecoinvent Centre, St-Gallen, Switzerland), and GaBi (PE International, Leinfelden-Echterdingen, Germany) database are useful to calculate the carbon footprint of a food system, as Minx et al. (2008) showed that the methodological expertise and software tools available could make it easier to research on quantifying carbon footprint of a food system.

Due to lack of relevant information and detailed dataset, it is difficult to offer an indication on a range of reduction that can be accomplished by using those methods described above. In addition, no single technology can provide all of the mitigation potential in any sector, meanwhile there are many technological and financial constraints to implement these methods (Bernstein et al., 2008). However, it is clearly acknowledged that reducing the gas emissions is an urgent and formidable issue, as Bernstein et al. (2008) showed that even if the concentrations of all GHGs and aerosols were kept stable at year 2000 levels, global averaged temperature would increase about 0.6 °C at 2090–2099 compared to 1980–1999.

CONCLUSIONS

A comprehensive food system involves several stages: raw material acquisition, processing, packaging, transportation, food preservation, and final consumption and disposal. In this review, methods to reduce the carbon footprint within the food system during these stages through LCA from the technical, behavior, and political perspective were discussed.

In general, improving management techniques, and adopting advanced technology and equipment are critical for every stages of a food system. Rational site selection is important to alleviate the influence of land use change. With an appropriate process control of carbon emission limit and process optimization, carbon emissions can be substantially decreased. In addition, environmental choices of package materials, size, and design have important effects on the total carbon footprint of the production. Besides, refrigeration consumes large energy during food transport and storage, reduction in refrigeration dependence is useful. Moreover, correct waste treatment is essential to reduce the carbon footprint of the final production, the energy from which can be exploited to reduce the use of fossil fuels. Furthermore, for consumer behaviors, choice for low carbon products can fundamentally amend the production methods and supply chains of the food industry, thus carbon labeling is a useful tool to control carbon footprint of the food chain. The reviewed literatures also give evidence showing that appropriate purchase patterns can reduce GHG emissions. Development of methods to calculate the carbon footprint of every kind of food and its processing technology enable people to make environmental choice. From political perspectives, government intervention and carbon offset are common tools in terms of climate change. Because the pursuit of economic profit is the main drive of industries during all the above stages, and a real or implicit price of carbon and carbon tax can give impetus to the development of low-carbon technologies, environmental policies therefore could be a solution to the dilemma of beneficial and cost. Due to some technological and financial obstacles, it is difficult to assess the overall outcome of these methods described above. However, these methods can slow down the process of climate warming to some extent.

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