CHAPTER 2

Mitigation of Greenhouse Gas Emissions in the Production of Fluid Milk

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Abstract Global climate change, driven by the buildup of greenhouse gas (GHG) emissions in the atmosphere, is challenging the dairy industries in the United States and throughout the world to develop sustainable initiatives to reduce their environmental impact. The U.S. dairy industry has committed to lowering the GHG emissions, primarily CH_4, N_2O, and CO_2, in each sector of the fluid milk supply chain which extends from the farm, to the processing plant, and to distribution of the packaged product, where it is refrigerated by the retailer and then the consumer. This chapter provides an overview of the life cycle analysis (LCA) technique and its use in identifying the GHG emissions in each sector of the fluid milk supply chain, from cradle to grave, and the best practices and research that is currently being conducted to reduce or mitigate GHG emissions in each sector. We also discuss the use of on-farm and off-farm process simulation as tools for evaluating on-farm mitigation techniques, off-farm alternative processing scenarios, and use of alternative energy management practices.

I. INTRODUCTION

The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007) stated with ''very high confidence'' that the effects of climate change are occurring due to anthropogenic (human-related) and natural activities that cause warming or cooling influences on global climate. Global warming is attributed to high concentrations of greenhouse gases (GHGs) in the atmosphere which absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds (IPCC, 2007). GHGs occur either naturally or are the product of industrial activity. The naturally occurring GHGs are water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone. Most of the observed increases in global average temperatures since the mid-twentieth century are *very likely* due to the observed increases in anthropogenic GHG concentrations (IPCC, 2007).

The atmospheric concentrations of GHG increase if emissions are greater than removal processes or mitigation processes. Human activities have resulted in increases in atmospheric concentrations of CO_2, CH_4, N_2O, and fluorinated gases, the group of gases containing fluorine, chlorine, or bromine, which are a product of industry. The IPCC reports that global increases in CO_2 concentrations are due primarily to fossil fuel use, with land-use change providing a significant but smaller contribution. It also reports that it is *very likely* that the observed increase in CH_4 concentration is predominantly due to agriculture and fossil fuel use. Increases in N_2O concentration are primarily due to agriculture. Fluorinated gases, such as hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, have increased to present levels from near-zero levels in preindustrial times.

Because of the different properties and lifetimes in the atmosphere associated with each of the GHGs, emissions are typically reported as teragrams (Tg), or million metric tons, of carbon dioxide equivalent, CO_{2eq}. The 100-year time horizon global warming potential (GWP) of CH_4 is 25 times as potent as CO_2, N_2O is 298 times as potent as CO_2, and the halocarbons range from 124 to 14,800 times as potent as CO_2 (IPCC, 2007).

Each year, the U.S. Environmental Protection Agency (EPA) recalculates and revises the inventory of U.S. GHG emissions and reports them in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA, 2009a). Energy-related data included in the report are obtained from the U.S. Energy Information Administration, U.S. Department of Energy (U.S. DOE/EIA-0573, 2008). In the United States, the majority of anthropogenic GHG emissions, on a million metric ton CO_{2eq} basis, are energy-related CO_2 emissions (81.3%) due to fossil fuel burning, CH_4 (10.5%), N_2O (4.3%), and other gases with high GWP (2.5%). Of the energy-related CO_2 emissions, petroleum is the largest fossil fuel source contributing 41.9% of emissions, followed by coal (36.5%) and natural gas (21.4%). Conversion of fossil fuel energy to electricity accounted for 40.6% of the energy-related CO_2 emissions. Transportation, with emissions coming from combustion of gasoline, diesel, and jet fuel accounted for 33.1% of the total emissions. Last, direct fuel use in the residential and commercial sectors and the use of fuels to produce process heat in the industrial sector accounted for 26.3 % of the total emissions.

Energy-related GHG emissions in the United States (million metric tons CO_2 equivalent) are also reported by the U.S. EIA (U.S. DOE/EIA-0573, 2008) in terms of the end-use sectors—residential, commercial, industrial, and transportation. Agricultural sources of GHG emissions are grouped under the industrial sector and are responsible for 6.2% of GHG emissions in the U.S. economy due to CH_4 and N_2O emissions and, to a much lesser extent, CO_2 emissions. Agricultural sources of CH_4 emissions include enteric fermentation in livestock, animal waste, rice cultivation, and crop residue burning. Enteric fermentation represents about 2% of the total U.S. anthropogenic GHG emissions with beef cattle responsible for about 72% of these emissions and dairy cattle about 23% in 2008 (EPA, 2009a). These emissions have increased from 2004 to 2007 due to a decrease in feed digestibility. Manure management represents about 8% of total CH_4 emissions. Agricultural soil management activities due to nitrogen fertilization of soils, solid waste of animals, and crop residue burning account for approximately 68% of N_2O emissions.

The FAO (2010) estimated that the entire dairy sector including both milk and related meat production accounts for 4% of anthropogenic GHG emissions across the world. The GHG emissions from global milk production, processing, and production were found to be 2.7% of the total. The global average GHG emissions of packaged milk were estimated at 2.4 kg CO_{2eq}/kg of milk, with the U.S. dairy industry contributing 45% fewer GHG emissions per kilogram of milk compared to the global average. The University of Arkansas in partnership with the Innovation Center for U.S. Dairy (www.usdairy.com) estimated that the U.S. dairy sector, cradle to grave and excluding dairy beef, accounts for less than 2% of U.S. anthropogenic GHG emissions (Thoma *et al*., 2010).

The dairy and other food processing industries have been challenged by their wholesale and retail customers to develop sustainable initiatives to reduce their environmental impact. These industries are unlike others in that their total contribution to GHG emissions are the sum of activities that arise not only from agriculture but also from fossil fuel use for energy used in milk production, processing, and transportation; chemical use for cleaning; plastics use for packaging; machinery manufacture; refrigerant use during shipping and sales; and waste. As separate measures of the GHG emissions associated with these activities are generally not available and thus not reported by the IPCC or EPA, dairy researchers are focused on quantifying the net GHG emissions in the various sectors of the dairy supply chain in an effort to gain insight on how they are generated and to develop methods to prevent or mitigate them. The best way to identify and quantify these emissions is through LCA methodology. The aim of this chapter is to provide the information published to date on the GHG emissions, or the carbon footprint, associated with a quantity of packaged milk at each stage of the dairy supply chain, and to report on the methods used or the research in progress to mitigate these emissions.

II. SUSTAINABLE DEVELOPMENT AND THE PILLARS OF SUSTAINABILITY

The Brundtland Commission of the United Nations, 1987, defined sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations, 1987). Sustainable development needs to meet three requirements, or pillars of sustainability—environment, social, and economic. The ''three pillars of sustainability'' is also known as the Triple Bottom Line (Marshall and Toffel, 2005) and is one of the leading sustainability frameworks. Several tools are available to assess the environmental aspects and impacts associated with an activity, the most popular being the LCA technique (ISO, 2006a,b) discussed later.

The Innovation Center for U.S. Dairy, which represents about 80% of the producers in the United States, has defined sustainability as providing consumers with the nutritious dairy products they want in a way that makes the industry, people, and the earth economically, environmentally, and socially better—now and for future generations. They have defined six pillars of sustainability—human health, energy, natural resources, community/economic prosperity, GHGs, and waste. Their current focus is on GHG emissions.

III. LIFE CYCLE ASSESSMENT METHODOLOGY

A life cycle assessment (LCA), also known as life cycle analysis, of a product or process begins with an inventory of the energy and environmental flows associated with a product from ''cradle to grave'' and provides information on the raw materials used from the environment, energy resources consumed, and air, water, and solid waste emissions generated. GHGs and other wastes, sinks, and emissions may then be assessed (Sheehan *et al.*, 1998). The net GHG emissions calculated from an LCA are usually reported per unit of product or as the carbon footprint.

The principles and framework for conducting the LCA have been developed by the International Organization for Standardization (ISO) in ISO 14040 (ISO, 2006a). An LCA consists of four components or phases—goal and scope definition, inventory analysis, impact assessment, and interpretation—as shown in Fig. 2.1. The goal and scope definition defines the purpose of the study, sets the boundaries of the study, and sets the reported unit of the product, that is, the functional unit of the LCA, such as a liter or gallon of milk. In the inventory analysis portion of the LCA, it is helpful to construct a flow diagram of the entire process to show all steps where there are inputs and outputs to the environment. Inputs and outputs include raw materials, mass, energy, air, water and solid waste emissions, and co- and by-products. GHG exchanges with the environment for the individual GHGs, such as CO_2, CH_4, and N_2O, are identified as well as the GHGs that are associated with the ''upstream''

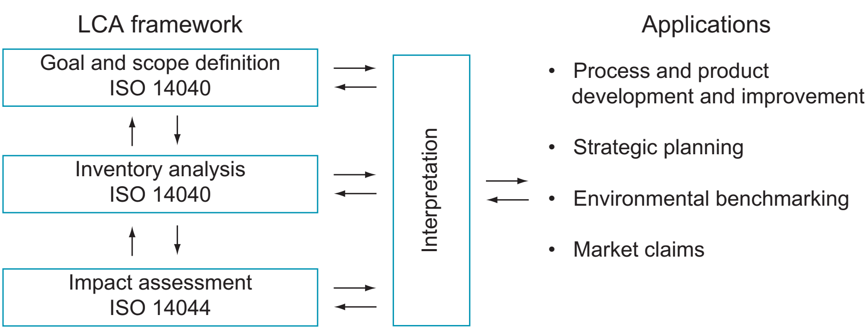

FIGURE 2.1 Life cycle assessment framework with applications.

production of materials, such as fuels, chemicals, plastics, feed, or machinery, that are processed or manufactured outside the defined process boundary. Flows that contribute less than 1% of overall emissions can be excluded. As an example, emissions associated with infrastructure (e.g., buildings, farm equipment, processing plants, and delivery trucks) commonly fall near the 1% cutoff line and are excluded. In addition, if valuable products other than the one of interest are produced, then allocation is required. ISO Standard 14040 provides a hierarchy of allocation procedures to follow for excluding co- and by-product GHG burdens. Finally, the net GHG emissions over the defined boundary divided by the total amount of a product produced yields the carbon footprint. For example, the results of an LCA for milk production may be reported as kg CO_{2eq}/kg of milk or lbs CO_{2eq}/gallon of milk.

The life cycle impact assessment (LCIA) is used to assess the results of the LCA and evaluate the impact on the environment in the various impact categories. These impact categories include, for example, human health, GWP, energy, water use, eutrophication, ozone depletion, aquatic toxicity, and land use (ISO, 2006b). LCA may focus on one or more impact categories. The results may be normalized, weighted, and aggregated in optional steps of the LCIA for comparison to political objectives, for example. In addition, sensitivity analyses are often conducted over the entire LCA to evaluate the variation in the results due to selected factors.

The interpretation step is for a reassessment of the inventory analysis, and the impact assessment is to assure that the goals of the study were met. The LCA has applications in process and product development and improvement, strategic planning, environmental benchmarking, and product marketing.

Commercial software packages are available for conducting an LCA. A list of software packages, databases, and additional information on conducting an LCA are found at the U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory Web site http://www.epa.gov/nrmrl/lcaccess/resources.html#Software.

IV. LCA OF THE FLUID MILK SUPPLY CHAIN

The consumption of dairy products plays a significant role in providing high-quality protein, vitamins, minerals, and other bioactive compounds to the American diet. Dairy products are consumed fresh in the United States in the form of fluid milk, cheese, yogurt, butter, and ice cream. Dried and condensed products such as nonfat dried milk, whey, whey protein concentrates, and isolates are also produced which are used as ingredients to boost the nutritional and functional properties of a host of other food products. The United States has over 1000 processing plants producing about 182 billion pounds of milk products/year with over 395 fluid milk plants producing over 57 billion pounds of fluid milk per year (IDFA, 2007) which contribute approximately $140B per year to the U.S. economy. The United States is the largest dairy producer in the world because of its production efficiency and state-of-the-art processing plants (US DEC, 2007) providing almost 20% of the world's milk supply.

Despite its efficiencies, the dairy industry has been singled out as the food-processing industry that has a significant environmental impact in terms of GHG emissions due to its dependence on animal agriculture (EPA, 2009a). With a growing U.S. and world population, it is expected that demand for dairy products will grow, further increasing the environmental impact of dairy.

To identify the effects of fluid milk production on GHG emissions, energy usage, and the other impact factors, LCA of the dairy supply chain extending from the farm to the consumer have been conducted by the dairy industries of several countries (Eide, 2002; IDF, 2005, 2009). Thoma *et al*. (2010) conducted the first comprehensive LCA study of the GHG emissions for fluid milk in the United States. Overall, the cradle to grave study found that the aggregate carbon footprint for fluid milk was 2.05 kg CO_{2eq}/kg of milk consumed. Their uncertainty analysis showed that the 90% confidence band ranged between 1.77 and 2.4 kg CO_{2eq}/kg of milk consumed. Total U.S. emissions were shown to be 35 Tg based on fluid milk consumed in 2007. Figure 2.2 provides the percentage of GHG emissions (region- and sales weighted) for each major unit contributor. The emissions were weighted based on milk production from farms within the five U.S. geographical regions and based on the fat content, that is, skim, 1%, 2%, and whole, of the purchased milk.

An LCA was also completed for an organic dairy in the United States extending from organic feed production to transport of the packaged liquid and product end-of-life disposal (Cashman *et al*., 2009). Overall GHG emissions were estimated at 7.98 kg CO_{2eq}/gallon (about 2.1 kg/kg) of packaged liquid milk, and the energy consumption over the entire system was 72.6 MJ/gallon of packaged milk.

Partial LCA for conventional and organic dairy farm systems, from the cradle to the farm gate, has been published for the Netherlands (de Boer, 2003), Sweden (Cederberg and Mattsson, 2000), Germany (Haas *et al*., 2001), and the United States (Rotz *et al*., 2010).

The goals of most LCA have been limited to determination of the impact of the fluid milk process on GHG emissions and energy due to the availability of relevant data and guidelines from the IPCC and other government agencies. Data for conducting LCA of the other impact factors such as water use, aquatic toxicity, human health, and land use are scarce, but new initiatives to reduce the impact of dairy production in

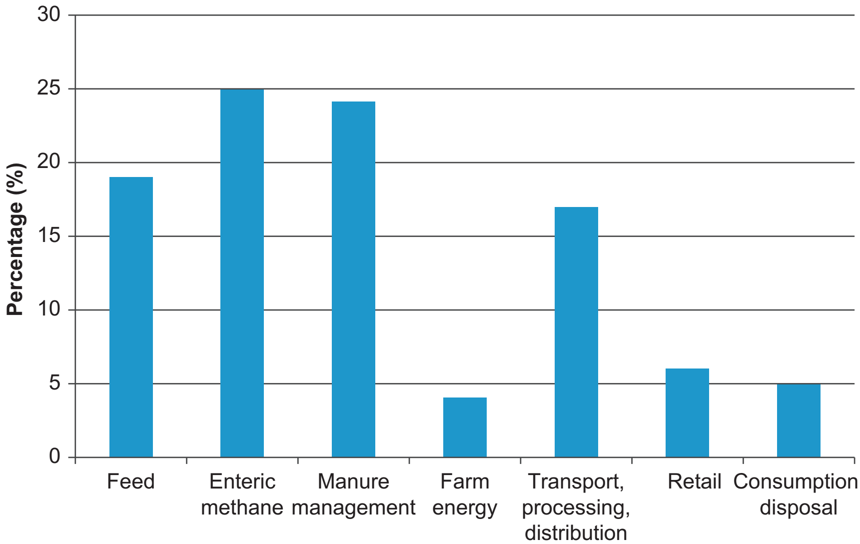

FIGURE 2.2 Percentage contributed by each unit process toward the total U.S. fluid milk emissions (Thoma *et al*., 2010).

Europe, Japan, the United States, and New Zealand will include these factors in future assessments (IDF, 2009).

A. LCA goal and scope definition

The goal of the LCA is to understand the impact of the existing fluid milk supply chain on energy usage and GHG emissions, as well as the other impact categories provided that data are available, and to use the information as a roadmap for improvements to the process. The LCA also provides an environmental benchmark to identify points where improvements to the fluid milk supply chain may be made.

The boundaries of the fluid milk supply chain are defined following the framework provided by ISO 14040 (ISO, 2006a). Milk production on the farm and milk processing in the processing plant are central operations in the fluid milk supply chain, but the system boundaries extend beyond the farm and the processing plant. For cradle to grave consideration, the system boundaries for LCA begin with crop production and end with retail sales as shown in Fig. 2.3 or may end with an end-of-life stage to account for disposal of the package. A time frame for the LCA is also chosen and is typically a 1-year period. As the LCA for the entire milk supply chain terminates with retail sales, the product of the LCA

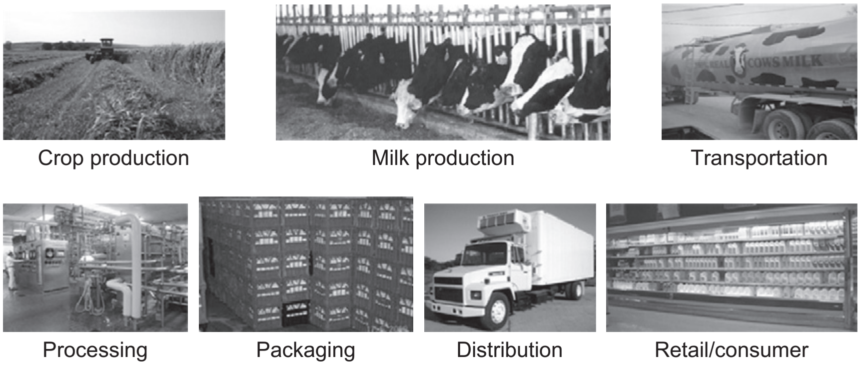

FIGURE 2.3 System boundaries for lifecycle analysis of the fluid milk supply chain.

may be reported in terms of the output as the GHG emissions associated with delivery of 1 gallon, 1 L, or 1 kg of packaged milk to the consumer which would capture the affect on GHG emissions of all sectors in the fluid milk supply chain. However, the product of the LCA may be input or output related and could also be reported in terms of the kilograms of raw milk produced or kilograms of raw milk processed. For comparison purposes, the output of milk is standardized using the energy corrected milk (ECM) or fat and protein corrected milk (FPCM) standardization formulas.

The formula for ECM may be used to standardize milk to 3.5% milk fat and 3.2% protein (Bernard, 1997):

$$\begin{aligned} \text{ECM(kg)} = {} & (0.3246 \times \text{kg of milk}) + (12.86 \times \text{kg of milk fat}) \\ & + (7.04 \times \text{kg of milk protein}) \end{aligned}$$

The FAO (FAO, 2010) uses the formula for FPCM used to standardize milk to 4.0% fat and 3.3% protein:

$$\begin{aligned} \text{FPCM(kg)} = {} & \text{raw milk(kg)}(0.337 + 0.116 \times \text{fat content (\%)} + 0.06 \\ & \times \text{protein content (\%)}) \end{aligned}$$

B. LCA inventory analysis

A complete inventory analysis is conducted for each segment of the fluid milk supply chain to account for all the resource inputs and the primary and secondary sources of GHG emissions (CO_2, CH_4, and N_2O) to air, water, and soil. The resource inputs include raw materials and energy. Their impact on GHG emissions are secondary sources of GHGs. The primary sources of GHG emissions are associated with farm operations.

1. Resource inputs

a. Crop production Crop production includes all the feed sources that are required to maintain the dairy herd and the resource inputs used to produce the crops. The type of feed depends on the animal management system—conventional or organic. Feeds may include mainly corn silage, corn grain, alfalfa hay and alfalfa silage, soybeans, soybean meal, wheat, oats, distiller's grains solids, with grasses, forage, and hay and dietary supplements such as minerals. The inventory would include the production of all feed crops raised on the farm, purchased from a vendor or other farm, or sold to another farm. In the United States, larger farms purchase feed while smaller farms grow their own feed (USDA Economic Research Service, 2007). A separate analysis would be conducted for the feed milling operations to account for its resource inputs such as fuel used in transportation and electricity. Other resource inputs in crop production include fuel for tractors and other equipment, water, machinery, fertilizer, pesticides, and packaging materials such as plastic and cardboard. Manure nutrients are a resource input if used in crop production unless some is removed for other uses outside of the production system (Rotz *et al.*, 2010).

b. Animal production/milk production Animal production and milk production include the care of cows and calves, animals sold or animals sold for meat, animals maintained off the farm, type of management system and number and breed of animals, type of animal housing, manure handling, milking parlor operations, and milk storage on the farm. Resource inputs include fuel, electricity, water, machinery, and packaging material.

Because dairy cows or calves are culled for meat production, four different methods to allocate the environmental emissions at the farm and outside the boundary of the fluid milk supply chain may be used (Cederberg and Stadig, 2003). The allocation method assumes, (1) no allocation is used and only milk production impacts the environment; (2) economic allocation assumes that emissions follow the yearly income derived from milk production and animals sold for meat production; (3) cause–effect physical (biological) allocation to account for the impact of the dairy cows' feed mix on milk production, calves, and meat; and (4) system expansion is used to expand the milk production system to also include meat production. Allocation methods may also be used if the milk is transported not only to fluid milk plants but also to plants processing other dairy products.

c. Transportation Transportation includes fuel used in movement of animals, materials, feed, and manure to the farm and may include the transportation of employees. It also includes the fuel used to transport milk to the processing plant. The insulated milk tanker, which is not refrigerated, has an average capacity of 6000 gallon and is a Class 8 heavy truck. It may travel to multiple farms to fill the tanker before delivery of the milk to the processing plant.

d. Milk processing Milk processing includes reception of milk with storage in refrigerated silos, followed by the steps associated with processing of milk such as milk separation, homogenization, and pasteurization; cleaning-in-place (CIP); and wastewater treatment. Plant maintenance may also be considered here as well as cool storage of packaged milk prior to transfer to warehouses, distribution centers, or retail stores. Allocation methods may be required if the plant is also used to process and package juice or other beverages and mixes. Furthermore, allocation may be required when excess cream is generated by the plant and sold or transported to another facility for manufacture of ice cream or butter and the system boundary is the plant boundary. Resource inputs include fuel for steam production, electricity, water, chemicals for CIP, packaging materials, and HFC refrigerants. Natural gas, propane, fuel oil #2, and diesel are the fuel sources used in most processing plants and the LCA would include all factors related to their extraction and production. Emission factors related to electricity use would be obtained using factors that are determined on a regional basis in the United States (Kim and Dale, 2005) for the regional electrical grids. The manufacture of the processing equipment and tools and other implements, which would represent embodied energy, may be included but is typically neglected due to their insignificant impact on emissions compared to their operational energy use. The transportation of employees to the plant and embodied energy in the construction of the plant may also be considered in the LCA but may be insignificant compared to plant energy usage.

e. Packaging Packaging includes the raw materials for the paperboard and plastic used to make the packaging materials for milk and container formation in the plant. Resource inputs include off-site raw materials manufacture, fuel, and electricity. The manufacture of the packaging equipment may also be considered to determine embodied energy. The filling operation is typically considered negligible or included as part of milk processing (Thoma *et al*., 2010).

f. Distribution Distribution of processed fluid milk in the United States may include temporary storage at the processing facility but more often includes transport to a cold storage site followed by distribution to retail stores. Refrigerated trucks make several trips between the milk processing plant and the cold storage site, returning empty to the processing plant.

Resource inputs include fuel used for the extensive travel, electricity for cold storage, and refrigerant.

g. Retail/consumer Milk is sold to customers from various types of retail stores which include convenience stores, supermarkets, and big-box warehouse stores. Packaged milk is transported from the plant or the cold storage site to retail locations in refrigerated trucks. At the point of retail, the milk is sold in refrigerated storage cases which may be open cases or enclosed ones with vertical glass doors. Energy requirements to operate and cool milk storage cases can vary significantly (Arthur D. Little, Inc., 1996). Consumer transport distance to purchase milk is also a factor. Resource inputs include mainly electricity at the retail location and in consumer homes, and fuel for transport of milk to the retail location and then to consumer homes. An LCA may also consider disposal of the product at a landfill or recycling facility.

2. Primary and secondary sources of GHG emissions

a. Farm *i. Estimation of N_2O emissions* Crop production is responsible for most of the N_2O emissions from the dairy farm which arise about equally from direct N_2O emissions from the soil; from animal waste management; and from indirect N_2O emissions through ammonia (NH_3), nitrogen oxides (NO_x), and nitrate losses (IPCC, 2006a). Direct N_2O emissions occur mainly through the nitrification and denitrification processes that occur in the soil. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). N_2O is the gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere (IPCC, 2006a). The reaction is controlled by the availability of inorganic N in the soil that results from anthropogenic N inputs or N mineralization (IPCC, 2006a). A model, known as the HIP or ''hole-in-the-pipe'' model, simulating the relationship between nitrification and denitrification (Davidson *et al*., 2000; Firestone and Davidson, 1989; Parton *et al*., 2001) shows that the rate of nitrogen cycling determines if the nitrification or denitrification mechanism is controlling. Soil moisture content mainly determines the rate of emissions of NO and N_2O. Reports of emissions of N_2O from cropped soils range from 1% (IPCC, 2006a) to 1.5% (Bouwman, 1996) of N inputs, and decreasing the N inputs to the soil could decrease N_2O emissions by the same amount. The rate of emissions of N_2O from grasslands is estimated as 2% (IPCC, 2006a). Only half of the N inputs are used in biomass and the rest is lost through leaching or in gaseous emissions of N_2, N_2O, NO_x, and NH_3 (Paustian *et al*., 2001).

Processes that produce N_2O emissions in soils also occur aerobically and anaerobically in bedded pack manure on bed floors, on manure-laden drylot surfaces, in slurry manure storage, and in stacked manure (Rotz *et al*., 2010). Application of the appropriate N_2O and N emissions factors are according to the IPCC (2006a). The contribution of manure to N_2O emissions is related to the exposed surface area and the amount of time that manure remains on surfaces. Manure removed daily from the floors of free stall or tie stall barns has a negligible contribution to N_2O emissions compared to bedded pack and drylot surfaces where manure remains longer and has a greater contribution to N_2O emissions. Chianese *et al*. (2009a,d) reported that N_2O emissions from manure storage were 0 to 0.1 kg N_2O m^{-3} of manure stored. Annual emissions from livestock facilities were also small and averaged 0.3 kg N_2O LU^{-1}. (LU is the Livestock Unit and is defined as 500 kg of live body mass.) The IPCC (2006b) also reports emission factors for calculation of N_2O emissions due to livestock. For an open slurry pond or tank with a crust, an emission factor of 0.005 kg of N_20-N/kg of N excreted is used. If a crust does not form, N_2O is not emitted and the emission factor is 0 (IPCC, 2006b). For the storage of manure in piles or stacks, the emission factor is 0.005 kg of N_20-N/kg of N.

Indirect emissions of N_2O are estimated separately from the direct emissions and occur by two pathways. In the first, volatilization of N as NH_3 and as oxides of N (NO_x) and their products $NH_4{}^+$ and $NO_3{}^-$ deposit onto soils and the surfaces of lakes and other waterways. In the second pathway, the leaching and runoff of N as $NO_3{}^-$ occurs. The estimates for total anthropogenic emissions that include both direct and indirect emissions of N_2O are estimated using net N additions to soils which come from synthetic or organic fertilizers, deposited manure, crop residues and sewage sludge, and N mineralized from mineral soil as a result of soil carbon. The IPCC (2006b) provides equations and emission factors for estimating aggregate total indirect N_2O emissions.

ii. Estimation of CH_4 emissions Dairy cows are the source of most CH_4 emissions from dairy farms. CH_4 is produced as a by-product of the microbial fermentation process in the rumen. The fermentation pathways were summarized by Moss *et al*. (2000) as follows:

$$\text{Glucose} \rightarrow 2\,\text{pyruvate} + 4\text{H}$$

$$\text{Pyruvate} + \text{H}_2\text{O} \rightarrow \text{acetate} + \text{CO}_2 + 2\text{H}$$

$$\text{Pyruvate} + 4\text{H} \rightarrow \text{propionate} + \text{H}_2\text{O}$$

$$2\,\text{acetate} + 4\text{H} \rightarrow \text{butyrate} + 2\text{H}_2\text{O}$$

$$\text{CO}_2 + 8\text{H} \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}\,(\text{methanogenosis})$$

Microorganisms break down the cellulosic feed fibers and plant carbohydrates into glucose and xylose monosaccharides. Oxidation of glucose produces pyruvate and H which is then fermented to produce the volatile fatty acids (acetate, propionate, and butyrate), CO_2 and H_2 (Moss *et al*., 2000). Enteric methanogens existing in the rumen use H_2 to form CO_2 and CH_4, releasing them to the atmosphere through respiration and eructation (Ulyatt *et al*., 1999). The extent of CH_4 production is influenced by the amount of feed intake and its digestibility, the size of the animal and type, and the composition of the diet—the amount of dry matter, total carbohydrates, and digestible carbohydrates (Monteny *et al*., 2001).

The IPCC (2006b) provides equations and emission factors for calculation of CH_4 emissions due to enteric fermentation and due to manure management system. Chianese *et al*. (2009a) reported that annual emissions of CH_4 from housing facilities, which are mainly due to enteric fermentation but also include the much lower source of CH_4 emissions from feces on the barn floor, ranged from 58 kg CH_4 LU^{-1} for dry cows to 106 kg CH_4 LU^{-1} for lactating cows. Lactating cows are expected to have larger emissions of CH_4 due to their larger feed intake. Dairy cows produce from 18 to 30 L of CH_4/h (Kinsman *et al*., 1995).

Emissions of CH_4 due to manure storage, which are functions of storage time and temperature, averaged 4.5 kg CH_4 m^{-3} with slurry storage twice that of stacked storage (Chianese *et al*., 2009a). Manure applied to cropland also provides a source of CH_4 emissions but typically disappears after a few days (Sherlock *et al*., 2002).

iii. Estimation of carbon dioxide emissions While agriculture is an important source of N_2O and CH_4 emissions, it is not a significant source of CO_2 emissions. The farm is a source of CO_2 emissions through respiration by animals, plants, and soil and decomposition of soil organic matter (SOM) and manure (Kirchgessner *et al*., 1991; Schlesinger and Andrews, 2000). Animal respiration, which results from conversion of the carbon in the animals' diet to CO_2 and CH_4 (Kirchgessner *et al*., 1991), accounts for approximately 90% of CO_2 emissions on the farm, followed by manure and fuel emissions (Chianese *et al*., 2009a), and is offset by CO_2 sequestered during plant growth, with 50% more CO_2 assimilated than emitted. Kinsman *et al*. (1995) reported that CO_2 released from housed lactating dairy cows ranged from 210 L/h to 310 L/h. An average net emission of -8345 kg CO_2 ha^{-1} $year^{-1}$ was reported for the CO_2 pathways that take place on a farm, with the negative value representing a flux into the system, an indication that plants capture more CO_2 by the process of photosynthesis than through respiration (Chianese *et al*., 2009a). Differences were noted for various types of crops with perennial crops sequestering more carbon than annual crops. Emissions from the same crop can vary from year to year due to dependence on climate and management practices. The IPCC does not report equations and emission factors for this category.

Long-term manure storage is a less significant source of CO_2 emissions through aerobic bacteria activity in the manure. CO_2 emissions were reported to average 59 kg CO_2 $m^{-3}year^{-1}$ (Chianese *et al.*, 2009a), although data were reportedly scarce.

To obtain CO_2 emissions related to fuel consumption on farms, fuel use for all farming operations including soil tillage, planting, harvesting of crops, feeding, and handling of manure requires monitoring. The carbon in fuels is converted to CO_2 produced through combustion. For diesel fuels which power tractors and most other fuel powered equipment on the farm, an emission factor of 2.637 kg CO_2/L was used to calculate CO_2 emissions (Chianese *et al.*, 2009a).

Resource inputs to the farm contribute to secondary CO_2 emissions with the smaller emissions due to N_2O and CH_4 typically converted to $kgCO_{2eq}$. Rotz *et al*. (2010) demonstrated calculation of these quantities in a partial life cycle analysis of a dairy production system. CO_2 emission factors to account for the production of fuel and electricity of 0.374 kg of CO_{2eq}/L of fuel and 0.73 kg of CO_{2eq}/kWh of electricity were calculated using the GREET model. Factors to estimate the electricity usage on the farm were obtained from Ludington and Johnson (2003). Electricity usage included that for milking activities, lighting, and ventilation. Electrical usage associated with ventilation including that for dry lots, naturally ventilated barns, and mechanically ventilated barns was also calculated using factors from Ludington and Johnson (2003).

Rotz *et al*. (2010) also calculated the CO_2 emissions associated with the initial manufacture of farm machinery and maintenance, with the emissions mainly associated with the energy used to produce and process steel. An emission factor of 3.54 kg of CO_{2e}/kg of machinery mass was used. Emissions associated with machines used to produce different types of feed and to handle manure for a small farm and larger farms were also calculated (Rotz *et al*., 2009). CO_2 emissions due to production of seed and plastics were found to be small.

In another approach to calculating energy usage and CO_2 emissions for a simulation of organic dairy operations, Cashman *et al*. (2009) converted energy consumption data for farm operations from utility bills and fuel usage sheets to GHG emissions from the grid to account for emissions on a regional basis in the United States (Kim and Dale, 2005). Emissions related to electricity usage ranged between 522.0 g CO_{2eq}/kWh in one region of the United States and 788.0 g CO_{2eq}/kWh in another. The variability in reported emissions was attributed to differences in the fuel makeup of coal, natural gas, fuel oil, and others at the electricity-generating plants in the two regions. The use of low-emission renewable energy sources such as hydroelectric, solar, wind, and nuclear power also reduces average emission rates per kWh of generated electricity. Further, transmission and distribution (T&D) losses for delivering electricity within major North American Electric Reliability Corporation's (NERC) grids ranges from 8.4% and 16.1% (Deru and Torcellini, 2007).

iv. Total farm GHG emissions inventory results There are a few reports of the total GHG emissions, or carbon footprint, associated with simulated or actual farm operations, from cradle to farm gate. Phetteplace *et al*. (2001) estimated that for simulated dairy systems with 1/2 of the total CO_{2eq} emissions from CH_4 and 1/3 from N_2O, the GHG emissions or carbon footprint of farm operations was 1.09 ± 0.2 kg CO_{2eq}/kg milk. Rotz *et al*. (2010) calculated N_2O, CH_4, and CO_2 emissions for simulated farms accounting for the effects of confined, grazing, or drylot management systems and location of the farm (Pennsylvania, PA or California, CA). The carbon footprint (kg CO_{2eq}/kg ECM) ranged from 0.46 for a 2000-cow drylot in PA to 0.69 for a 60-cow confined PA farm. Cashman *et al*. (2009) reported that the carbon footprint (kg CO_{2eq}/kg of ECM) at the farm gate for six organic farms ranged from 1.10 to 1.88 with the differences attributed to manure management and feed transport. Thoma *et al*. (2010) reported that the United State's national average GHG emission was 1.23 kg CO_{2eq}/kg FPCM at the farm gate. The carbon footprint at the farm gate for North America (FAO, 2010) was approximately 1.0 kg CO_{2eq}/kg FPCM. The carbon footprint at the farm gate ranges from 1.3 to 7.5 kg CO_{2eq}/FPCM in different regions throughout the world (FAO, 2010). Feed production, manure management, and enteric CH_4 are the major contributors to GHG emissions at the farm.

b. Transportation from the farm to the milk processing plant GHG emissions for transport of milk from the farm to the processing plant occur solely from combustion of diesel fuel which converts the carbon in the fuel to CO_2 and depend on the distance from the farm to the processing plant. Based on guidelines from the IPCC that require an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized to CO_2, the EPA (2005) calculated that the CO_2 emissions from a gallon of diesel fuel are 22.2 pounds/gallon.

Based on over 200,000 round trips and data from 37 states, Thoma *et al*. (2010) reported that transporting raw milk from U.S. farms to processing plants resulted in GHG emissions or a carbon footprint for transportation of 0.20 kg CO_{2eq}/gal of milk delivered. Cashman *et al*. (2009) reported that the carbon footprint associated with raw milk transport ranged from 0 to approximately 0.9 kg CO_{2eq}/kg ECM and an average of 0.13 kg CO_{2eq}/gallon of milk depending on the distance of the farm from the processing plant.

c. The milk processing plant GHG emissions from the processing of fluid milk are mainly due to CO_2 and perfluorinated hydrocarbons. They result from the energy used to pasteurize and process the raw milk, and from the use of refrigerants. In a typical processing plant in the United States, the primary forms of energy used are electricity, natural gas, propane, fuel oil #2, and diesel. Electricity is used by the refrigeration system, air compressors, chillers, fans, pumps, and other equipment, while heating fuel is used by the boiler and hot water heating systems.

High-temperature short time (HTST) pasteurization is used in a majority of plants in the United States. HTST pasteurization is conducted at temperatures >72 °C and holding time ≥ 15 s in the United States (FDA, 2009). Milk may also be pasteurized using ultrahigh temperature (UHT) pasteurization.

HTST pasteurization is central to milk processing and has a large heat demand due to the high flow rates and short residence times used. HTST pasteurization is accomplished using a plate heat exchanger. Raw milk at 4 °C is fed to a balance tank to maintain a constant level of milk and then fed to the regeneration section of the pasteurizer. The milk is heated to approximately 63 °C by a countercurrent flow of pasteurized milk. The milk is then separated (standardized) to make milk of varying fat contents and then homogenized. The milk then enters the heating stage of the pasteurizer where it is heated by the countercurrent flow of hot water to a minimum pasteurization temperature of 72 °C and held for a minimum of 15 s. The hot water is heated by steam. The milk then flows to the regeneration section of the pasteurizer to heat the incoming raw milk and is then cooled to below 4 °C by water chilled using coolant in the plate heat exchanger. The separated cream may be pasteurized on site using HTST or UHT pasteurization or shipped to another plant for processing. CIP procedures are implemented daily to remove milk residues. The CIP process consists of flushing the pasteurization system with hot water and then following with a timed sequence of flushes by hot alkali solution (sodium hydroxide) and hot acid solution (nitric acid) wash steps to remove protein and carbohydrates. A sanitizer may also be applied. These operations are conducted using high volumes of cleaning solutions and may be conducted for up to 6 h a day to ensure the proper performance of the pasteurization equipment, product quality, and particularly product safety.

Some information on total energy consumption of fluid milk processing plants around the world is available but is not segmented to account for energy use of each unit operation. Xu and Flapper (2009) characterized energy use to assess specific energy consumption (SEC) levels, defined as the primary energy or final energy (end use), divided by the production quantity of the fluid milk product. SEC may be calculated for energy use of an entire plant or for energy use of each unit operation if available. The lower the value of SEC, the more energy efficient the process. Xu and

Flapper (2009) calculated SEC for 17 fluid milk plants in the United States and other dairy-producing countries using data from the U.S. DOE (2010). The calculated SEC ranged from 0.2 to 6.0 MJ/kg of milk. The values of SEC for a particular plant, when segregated into those using a greater percentage of SEC from fuel versus a greater percentage from electrical energy, varied from region to region and with climate and other factors. It was suggested that the lower end of the SEC ranges could be used as a starting target for best practice benchmarks. The data were not converted to carbon footprint because of uncertainty in allocation of the milk products resulting from fluid milk processing.

Benchmarking by process step is also useful to identify the unit operations with the highest energy demand in a plant and would provide information for process improvements. In a comparison of processing plants in Canada and the Netherlands for which data were available, Xu and Flapper (2009) showed that milk treatment including separation and pasteurization accounted for most of the energy used in processing in both plants. Cooling and refrigeration was second in the Netherlands but negligible in the Canadian plants. CIP was also an important contribution to energy use in both plants.

Energy use in the form of electricity is approximately 70% of the energy used in processing plants and fuel is approximately 28% of the energy used (Thoma *et al.*, 2010). Coal, a significant emitter of GHGs when burned, is the primary fuel source for generating electricity within the United States. By the time electricity is generated, arrives at the processing plant, and is used by equipment such as lighting and motors; only a small portion of actual energy has become useful work. The remainder has been lost along the way via inefficiencies and dissipates to the ambient as heat. The majority of heating fuel requirements in processing plants was attributed to steam production. Natural gas was used in most cases in boilers to generate steam for pasteurization and cleaning. GHG emissions in the processing plant due to electricity use were reported as 0.054 ($\pm$0.0090) kg CO_{2eq}/kg of packaged milk and that due to fuel use was 0.022 ($\pm$0.0044) kg CO_{2eq}/kg of packaged milk (Thoma *et al.*, 2010).

Cashman *et al.* (2009) reported that the total energy use attributed to dairy plant utilities (plant natural gas, electricity, water, and wastewater treatment) was approximately 8.5 MJ/gallon of milk (2.2 MJ/kg of milk). However, the milk was processed using ultrapasteurization which has higher energy requirements than HTST pasteurization due to the higher temperatures used. The corresponding GHG emissions, or carbon footprint, were reported as about 0.45 kg CO_{2eq}/gallon of milk (0.12 kg CO_{2eq}/kg of milk). The FAO (FAO, 2010) reported that, for North America, calculated GHG emissions are 0.225 kg CO_{2eq}/kg FPCM milk at the farm gate, which includes transport from the farm to the dairy, processing, packaging, and transport from the dairy to retail. This value is lower than that estimated by the U.S. dairy industry for milk processing alone.

High heat CIP operations that are conducted at temperatures of 71 °C account for more than half the fuel demands of a fluid milk processing plant (Innovation Center for U.S. Dairy, 2008). Eide *et al*. (2003) conducted an LCA to compare the conventional CIP process to three other methods for the impact categories energy use, global warming, acidification, eutrophication, and photo-oxidant formation. CIP methods with small volumes and low temperatures, such as enzyme-based cleaning and one-phase alkaline cleaning, as well as membrane filtration, were the best alternatives to conventional CIP for reducing energy use. Milk residues flushed out in the rinsing phase were the main contributor to eutrophication. Phosphorus and nitrogen in the detergents also influenced the results.

Treatment of dairy waste streams from CIP and other operations is not a significant portion of plant energy use, but waste from the dairy industry can contribute to the pollution of water and soil (Kosseva, 2009).

Loss of GHG refrigerants in the processing plant for milk cooling and storage of packaged milk prior to distribution are essentially negligible and have been estimated to contribute to less than 1% of GHG emissions or 0.001 kg CO_{2eq}/gallon of bottled milk (Thoma *et al*., 2010). The majority of milk cooling is provided by ammonia-based refrigeration systems and not HFC refrigerants. Ammonia is not a GHG, so losses do not result in GHG emissions. The manufacture and delivery of ammonia refrigerants would require a small amount of GHG emissions.

d. Packaging Milk is packaged in the United States predominantly in plastic (85%) containers and paperboard (15%). The plastic category includes the rigid blow molded or thermoformed containers, single-serve round containers, plastic-lined boxes consisting of a polyethylene bag in corrugated paper box or in a rigid plastic case and plastic bags sold separately. The paper category includes wax- and plastic-coated containers and foil-lined UHT containers. Less than 0.5% of milk is packaged in glass (USDA AMS, 2005). The largest proportion of fluid milk sales are in high-density polyethylene (HDPE) gallon jug containers representing 65% of total sales.

GHG emissions for milk packaging are mainly CO_2 and arise from the energy used to process and produce the raw materials, container formation which is done on site in fluid milk plants and from transportation of the raw material (Innovation Center for U.S. Dairy, 2008; Keoleian and Spitzley, 1999; Spitzley *et al*., 1997).

The rigid plastic milk bottles are made in the dairy processing plant using blow molding. In this process, HDPE pellets are fed from a hopper into an extruder where they are heated by shear and heat to soften them.

They are then forced through a narrow die to form a hollow tube called a parison. A chilled mold is then clamped around the parison and inflated from the inside by air. The air pressure presses the parison against the mold, and it hardens in the shape of the mold. The mold then opens and ejects the HDPE bottle. The bottle is then trimmed and conveyed to the milk filling station. The waste plastic is ground for reuse. GHG emissions associated with the embodied energy of the packaging machinery may be calculated but typically fall near the 1% cutoff line and can be excluded (Cashman *et al*., 2009).

After filling, the plastic gallon containers are packaged in secondary packaging such as milk crates with 4 gallons per crate. Larger amounts of the gallon containers may be packed in corrugated cardboard boxes, placed on pallets, and then shrink-wrapped using LDPE film.

GHG emissions associated with the raw material are determined from the energy used to manufacture the plastic materials and the fuel used to transport them to the plant. The transportation and manufacture of the secondary packaging used to transport the primary raw materials and finished materials may also be considered. The embedded energy of the materials, if made from petroleum products, is also accounted for when it is used as a raw material (Keoleian and Spitzley, 1999; Spitzley *et al*., 1997). End-of-life emissions may also be included in LCA of milk packaging and include the energy used to recycle the package or emissions in the form of CH_4 from a landfill.

Thoma *et al*. (2010) reported that the production of the raw material was found to be associated with 63% of emissions, while container formation was associated with 37% of emissions. Emission rates for raw material manufacture and delivery were determined to be 0.034 ($\pm$0.0034) kg CO_{2eq}/kg of packaged milk, while the container formation was 0.020 ($\pm$0.0012) kg CO_{2eq}/kg of packaged milk.

Packaging of milk in either 1 gallon blow molded bottles or 1/2 gallon paperboard packaging was found to be associated with 0.46 kg CO_{2eq}/gallon of milk (0.12 kg CO_{2eq}/kg of milk), representing 44% of GHG emissions and 48% of energy consumption in the milk processing stage (Cashman *et al*., 2009). Energy consumption used in packaging was reported as 10.0 MJ/gallon of milk.

Packaging in 1/2 gallon HDPE bottles, the most common packaging type over the region that includes the United States, Canada, and Mexico, was associated with 91 g CO_{2eq}/L of milk (0.35 kg CO_{2eq}/gallon or 0.76 lbs CO_{2eq}/gal) (FAO, 2010), which is consistent with the values reported by the U.S. dairy industry and Cashman *et al*. (2009). GHG emissions associated with HDPE bottling are greater than those reported for other packaging types used in other regions of the world. The 1-L plastic pillow pouch used in the former Soviet Union and Southern Asia/Mediterranean Africa was associated with an average of 22 g CO_{2eq}/L of milk. The carton gable top, chilled, 1-L, used in Northeast Asia and Oceania is associated with 38 g CO_{2eq}/L of milk, and the 1-L carton brick, used to package UHT milk, is associated with an average of 59 g CO_{2eq}/L of milk.

e. Transportation and distribution of packaged milk After packaging, the milk is transported to cold storage sites, retailers' distribution centers, or directly to the retail center, normally using refrigerated Class 8 trucks. The milk is then transported to various retail sites. GHG emissions during distribution occur mainly from diesel fuel use. Total emissions were reported (Thoma *et al*., 2010) to be 0.072 ($\pm$0.0102) kg CO_{2eq}/kg of packaged milk. Diesel fuel use made up 81%, while losses in truck refrigerant contributed 29% or 0.014 ($\pm$0.0037) kg CO_{2eq}/kg of packaged milk. The refrigeration emissions during cold storage or at the distribution center were not reported.

Cashman *et al*. (2009) reported that the distribution stage contributed to 9% of the total GHG emissions of the overall milk life cycle, with transport of milk to cold storage, refrigeration, transport to distribution centers, and transport of the empty tractor trailer back to the plant accounted for about 0.9 kg CO_{2eq}/gallon of milk. Refrigeration at the distribution center and transport to the retail centers accounted for about 0.2 kgCO_{2eq}/gallon of milk. Refrigeration GHG emissions during cold storage of milk alone accounted for about 0.09 kg CO_{2eq}/gallon of milk and, at the distribution center, about 0.11 kg CO_{2eq}/gallon of milk.

f. Retail GHG emissions associated with retail sales of milk accounted for approximately 5% of the total CO_{2eq} in fluid milk or 0.099 kg CO_{2eq}/kg of milk consumed. At the retail level, 64% of these emissions were due to electrical energy use, 36% were due to refrigerant emissions of HCFC, and less than 1% were due to natural gas space heating (Thoma *et al*., 2010). Waste from spoilage and spillage was assumed to be 12%, while refrigerant losses were considered to be nearly 20% of annual charge per year. Emissions due to consumer refrigeration were not reported.

Cashman *et al*. (2009) reported that GHG emissions at the retail location were approximately 0.15 kgCO_{2eq}/gallon of milk. Consumer refrigeration accounted for 51% of all milk GHG refrigeration emissions and showed the greatest energy consumption of all the refrigeration processes. GHG emissions at the consumer level were reported as 0.35 kgCO_{2eq}/gallon of milk.

C. Life cycle impact assessment

Figure 2.4 compares the GHG emissions in different sectors of the fluid milk process from three LCA analyses performed for U.S. dairy farms. The Cashman *et al*. (2009) study was conducted using primary data from farmers and processors for organic operations. The Thoma *et al*. (2010) study utilized

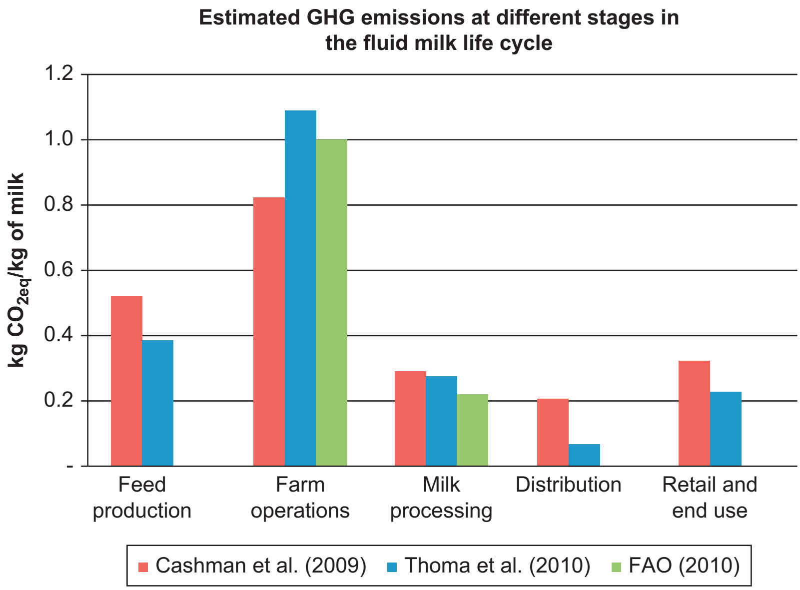

FIGURE 2.4 Comparison of GHG emissions from LCA analyses of U.S. dairy operations. The FAO results are reported for North America and were not available for all sectors.

primary data from surveys of farmers and processors across the United States, and a mixture of other sources. The FAO (2010) study was conducted using literature data for North America. The differences reported for each sector from the three LCA analyses arise not only from the types of data utilized in the respective studies but also from differences in the goal, scope, boundaries, and assumptions used to perform each LCA.

Figures 2.2 and 2.4 indicate that farm operations which include feed production, manure management, and enteric CH_4 are areas where mitigation strategies are required to lower GHG emissions and the carbon footprint of milk. Even though most GHG emissions arise from farm operations, mitigation strategies at the milk processing, distribution, and retail sectors that reduce fuel, refrigerant, and electricity use would also reduce GHG emissions and energy use.

V. ON-FARM GHG EMISSION MITIGATION STRATEGIES

A. N_2O mitigation strategies

Because the nitrification and denitrification processes both form N_2O as a by-product, control of anthropogenic N inputs to the soil in the form of synthetic fertilizers or manure would affect the amount of N_2O produced and lost. N inputs may be optimized by balancing the crop requirements for N and crop growth with availability of N in the soil through agronomic practice, nutrient management or soil management. Some methods for mitigation of N_2O emissions are shown in Table 2.1 (Liu *et al.*, 2006; Marland *et al.*, 2001; Paustian *et al.*, 2001; Smith *et al.*, 2007).

Stored manure, manure on floors of housing facilities using bedded pack, or drylot manure are not significant sources of N_2O emissions, but

TABLE 2.1 Recommendations for mitigation of N_2O

Source	Mitigation	Result
Crop production	*Agronomic practice*	
	Rotation with cover crops	Extracts N from previous crop reducing N_2O emissions
	Nutrient management	
	Apply N based on crop needs	Precision farming techniques
	Apply controlled release fertilizers or nitrification inhibitors	Inhibit processes leading to N_2O formation
	Apply N prior to plant uptake	Increases yield
	Apply N precisely into the soil to improve accessibility to crops	
	Land/water management	
	Improvement of physical soil conditions to reduce soil wetness	Inhibit processes leading to N_2O formation
	Limit soil compaction through tillage, traffic, and animals	Reduce conditions for denitrification
Manure	*Manure handling*	
	Manure storage	Maintain under anaerobic conditions
	Examine use of straw-based or deep litter systems	Consider anaerobic slurry-based systems
	Minimize grazing periods to limit urine spreading	Slurry spreading results in lower N_2O emissions
	Use N fertilization practices above	Reduce losses to N_2O production and leaching

Adapted from Paustian *et al.* (2001), Monteny *et al.* (2006), and Smith *et al.* (2007).

the nitrification and denitrification processes that occur in soils may also occur in manure under certain conditions. Mitigation practices (Table 2.1) include maintaining the manure under anaerobic conditions. Also, compaction to reduce contact with oxygen has been suggested but has been shown to have mixed results in reducing N_2O emissions (Monteny *et al.*, 2006; Smith *et al.*, 2007).

B. CH_4 mitigation strategies

The milk production stage is the largest source of GHG emissions over the entire life cycle of fluid milk production. CH_4 is generated primarily through enteric fermentation of dairy cows and also through the microbial, anaerobic decomposition of manure. Manure deposited on soil or handled as a solid, an aerobic process, emits little CH_4. However, manure generates CH_4 when stored under the aerobic conditions of a lagoon.

Several practices have been suggested to reduce enteric CH_4 emissions and emissions from waste. These include improving feeding practices, use of dietary supplements, vaccines, improving livestock management, improving manure management, and production of biofuels.

1. Reduction of enteric CH_4 emissions

Improved feeding practices are aimed at reducing H_2 production used in the methanogenesis process to produce CH_4 (Moss *et al.*, 2000). Increasing the amount of feed intake may reduce CH_4 by 1.6% of the gross energy intake (Johnson and Johnson, 1995). Feeding more digestible carbohydrates can influence the relative production amounts of the fermentation products. Starch-based diets favor production of propionate (Johnson and Johnson, 1995) and pass through the rumen more quickly than insoluble or cell wall carbohydrates (Johnson *et al.*, 1996). Increasing the level up to 25% can decrease CH_4 by up to 20% (Moss *et al.*, 2000), but there may be detrimental effects such as acidosis, laminitis, and fertility problems. Concentrates may also be used to favor production of propionate to decrease CH_4 production (Smith *et al.*, 2007) although addition of concentrates was not found to decrease CH_4 emissions in other instances (Pinares-Patiño *et al.*, 2009). Improving quality of feeds through improvement of forage quality can also lower CH_4 production (Boadi *et al.*, 2004) and increase the energy used for production. The ensiling process for forage preservation results in fermentation which can reduce rumen digestion, possibly reducing CH_4.

Addition of oils and oilseeds to the diet is another method that has been used to reduce CH_4 emissions (Beauchemin *et al.*, 2008; Eckard *et al.*, 2010). Lipid addition to the diet may reduce CH_4 emissions by hydrogenation of unsaturated fatty acids, enhanced propionic acid production, and protozoal inhibition (Johnson and Johnson, 1995). Reductions in CH_4 of $\geq$40% have been demonstrated with lipid supplementation

(Beauchemin *et al.*, 2008) and depend on the level of supplementation, the lipid source and fatty acid profile, and the type of diet.

Several dietary additives and specific agents have been proposed to affect the methanogenesis process or the methanogens directly (Beauchemin *et al.*, 2008; Eckard *et al.*, 2010; Smith *et al.*, 2007). These include ionophores, halogenated compounds, plant compounds, probiotics, propionate precursors, vaccines, and bovine somatotropin (bST). Ionophores are a class of antibiotics that are not used therapeutically, such as monensin, that decrease the ratio of acetate to propionate to reduce CH_4 production. These results though are transitory (Johnson and Johnson, 1995). The EU has banned antimicrobial feed additives such as the ionophores. Halogenated compounds inhibit CH_4 formation but the benefits are also transitory. Novel plant compounds such as condensed tannins (CT), saponins, and essential oils (Benchaar *et al.*, 2008; Calsamiglia *et al.*, 2007; Martin *et al.*, 2010) are of interest as alternatives to antimicrobials for reducing CH_4 emissions. CT, which are polyphenolic compounds, have been shown to reduce CH_4 production by 13–16% (DMI basis) by having a toxic effect on the methanogens (Eckard *et al.*, 2010), but high concentrations of CT can reduce fiber digestibility and animal productivity (Beauchemin *et al.*, 2008). Not all CT are effective in cattle, and testing of each may be necessary (Martin *et al.*, 2010). Saponins are glycosides that have an antiprotozoal effect, which eliminate the methanogens associated with the ruminal ciliate protozoa (Holtshausen *et al.*, 2009) and have demonstrated reduction in GHGs in sheep by up to 40% (Hess *et al.*, 2004). While the use of CT and saponins have shown a reduction in CH_4 emissions in many cases, the variability in the sources, and the expense of the compounds can be a barrier to practical use. Essential oils, such as garlic, cinnamaldehyde, and eugenol, inhibit the growth of some bacteria and some have been shown to inhibit deamination and methanogenesis. However, more research is necessary to determine the optimal dose, adaptation of microbial populations and animal performance, as well as the potential for residues in the meat and milk of the animals (Calsamiglia *et al.*, 2007).

Stonyfield farms, a commercial processor in the United States, has initiated a ''Greener Cow Project'' to decrease CH_4 emissions by feeding cows a diet rich in natural omega-3 sources http://www.stonyfield.com/search/index.jsp?q=greener+cow&x=12&y=8. Preliminary results indicate a reduction of enteric emissions by an average of 12% and an increase in omega-3 fatty acids in milk.

Probiotics have also been suggested as a means to potentially lower CH_4 emissions. Few studies have demonstrated the use of yeast (McGinn *et al.*, 2004; Newbold and Rode, 2006), but further research is required to develop a yeast that improves fermentation and animal performance as well as reduces CH_4 emissions (Beauchemin *et al.*, 2008). Preliminary research has also shown that fermentation products containing enzymes such as cellulases and hemicellulases can improve the digestion and productivity of animals (Beauchemin *et al*., 2008) and lower CH_4 production through fiber degradation.

Propionate precursors are dicarboxylic acids such as fumarate and malate that reduce methanogenesis by acting as H_2 acceptors. Reductions in CH_4 emissions as high as 75% in sheep (McAllister and Newbold, 2008) were achieved by feeding with a diet that included 10% fumaric acid encapsulated in fat for slow release into the rumen. However, reductions in CH_4 emissions for beef cattle or dairy cattle fed lesser amounts of organic acids, as a percentage of the diet, were not significant. It was concluded that supplementing diets with organic acids is uneconomical due to the high concentrations required.

Vaccines against methanogenic bacteria (Williams *et al*., 2009; Wright *et al*., 2004, 2006) are a novel approach for reducing CH_4 emissions from livestock with the potential to specifically target methanogens in the rumen. Wright *et al*. (2004) noted a 7.7% reduction of CH_4 emissions in sheep after vaccination with a three strain preparation of methanogens. Methanogen populations in the rumen are influenced by factors such as diet and environment and less than 20% of the methanogens detected in the sheep were related to the vaccine. In a later study (Williams *et al*., 2009), vaccination induced a serum antibody response against methanogens in sheep but did not affect CH_4 emissions; however, the vaccine affected the diversity and composition of the methanogen population. Results suggested that a broad-spectrum approach is needed in the rumen to target methanogens.

A number of additional methods have been proposed to target CH_4 emissions such as the use of bacteriophages and bacteriocins (McAllister and Newbold, 2008), defaunation, and reductive acetogenesis (Martin *et al*., 2010; McAllister and Newbold, 2008). Additional research is needed as well as animal trials for potential use on dairy farms.

The use of recombinant bST does not reduce GHG emissions but increases milk production so that the calculated emissions/unit of milk produced is reduced (Baumann, 1992). Capper *et al*. (2008) evaluated the environmental impact of using bST in a conventional dairying system and reported reductions in CH_4 emissions of 8.3%. 15.2% of the total of small (<100 cows), medium ($100 < \text{cows} < 500$), and large farm operations ($\text{cows} > 500$) surveyed in the United States used bST on 17.2% of the cows (USDA, 2007). The use of bST increased with the size of the operation, with 9.1% of small farms using bST and 42.7% of large farms reporting use of bST.

Improved management practices that lead to increased animal productivity have been proposed as a method to reduce CH_4 emissions per unit of milk (Boadi *et al*., 2004). Approximately 50% of feed energy is for animal maintenance with the remainder used in production. As productivity increases, CH_4 emissions will go up but the calculated emissions/unit of milk decrease. Due to the increased productivity, fewer animals are required to produce a given quantity of milk. Modeling studies in the UK showed that breeding dairy cows for traits such as growth rate, milk production, fertility, and efficiency of feed conversion resulted in decreases in GHG production per unit of animal product by about 1% per year and that it was predicted that these trends will continue into the future at least at the rate of the previous 20 years (Gill *et al.*, 2010).

2. Manure management

Manure management involves various technologies for collection, handling, storage, treatment, and land application (Powell *et al.*, 2010) which are chosen based on the size of the herd, soil type, climate, and other factors such as available labor. Technologies that have been proposed to reduce CH_4 emissions include cooling the emissions from manure stored in lagoons or tanks, the use of lined and covered manure storage, separating solids from slurry, and by capturing emitted CH_4 (Smith *et al.*, 2007). Technology alternatives such as filter strips and concrete pads with retaining walls for stacking manure have been proposed as more economical options for the small farmer (Powell *et al.*, 2010). However, implementation of technologies to reduce CH_4 emissions can be complex, as reduction strategies to lower CH_4 emissions can also enhance N_2O and CO_2 emissions (Chianese *et al.*, 2009c; Martin *et al.*, 2010). They may also be difficult for small farms to adopt due to labor considerations and technologies costs (Powell *et al.*, 2010), but most are affordable for medium and large farms.

3. Anaerobic digestion and thermochemical conversion of manure

The shift to larger and more modern dairy farms in the United States and the management techniques needed to operate them may lead to less pollution due to economies of scale (Norris and Batie, 2000; Powell *et al.*, 2010). A greater percentage of manure is collected on mid- and large-sized dairy farms and this advantage may be exploited to recover CH_4 from manure using anaerobic digestion. Anaerobic digestion, an established technology, is a biological process in which bacteria break down the manure to produce a gas stream consisting of about 60–70% CH_4, 30–40% CO_2, hydrogen sulfide (H_2S), and a nutrient-rich effluent. It also has the advantage of eliminating pathogens, if present, in the manure. The biogas may be used as fuel or to fuel generators to produce steam and electricity. The gas should be refined to produce biomethane gas with removal of CO_2 and H_2S, which is corrosive. The digested solids and liquid from the manure may be used as soil amendments or fertilizers. Due to its complexity, the digester requires on-site management.

There are three main types of digesters—covered lagoons, complete mix, plug flow and also anaerobic sequencing batch reactors, and fixed film reactors (Balsam, 2006; Bunting, 2007; Cantrell *et al*., 2008; Singh and Prerna, 2009). The AgStar program, a consortium of the U. S. Departments of Agriculture and Energy and the Environmental Protection Agency, provides detailed information on the planning, operation, installation, and economics of anaerobic digestion (http://www.epa.gov/agstar/pdf/manage.pdf). It has been estimated that anaerobic digestion would be cost-effective on 7000 farms in the United States. Liebrand and Ling (2009) recommend cooperative approaches for operation of anaerobic digesters for cost effectiveness.

Cuellar and Webber (2008) estimated that manure from 95,000,000 animal units (1000 pounds of animal) in the United States could produce approximately 1% of total U.S. energy consumption. Conversion of the biogas into electricity could produce $2.4 \pm 0.6\%$ of annual electricity consumption with reduction of $3.9 \pm 2.3\%$ of annual GHG emissions from electricity generation in the United States.

Thermochemical conversion (TCC) uses high temperatures to break apart the bonds of organic matter and reform the intermediates into oil, gas, and char (Cantrell *et al*., 2008; Wingsley, 2007). There are three types of TCC: pyrolysis, gasification, and direct liquefaction. Little information is available on the use of TCC for conversion of dairy manure. Pyrolysis involves burning biomass in the absence of oxygen at temperatures greater than 400 °C. The products of pyrolysis are bio oil and bio char. Bio oil contains about 42% of the energy content of fuel oil (Wingsley, 2007). The bio oil maybe converted to diesel fuel and the bio char has value as a substitute for activated carbon and as a soil amendment which may enhance soil carbon sequestration. The pyrolysis process is currently of the most interest because it has the potential for simple on-farm processing of manure and of other waste, with off-site removal for further purification of the oil at a biorefinery. Pyrolysis of biomass is currently being investigated at research centers throughout the United States (U.S. DOE, National Renewable Energy Laboratory and the USDA, Agricultural Research Service).

Biochar from dairy manure also has potential for environmental remediation or for creating slow release phosphorus fertilizers (Cau and Harris, 2010). Dairy manure was converted by heating at temperatures below pyrolysis temperatures (<500 °C) and in the presence of air. The potential benefit for lowering GHGs was not determined but the products have the potential of creating new markets for manure.

C. CO_2 mitigation strategies

Although most CO_2 emissions at the dairy farm are due to animal respiration, these emissions are largely offset by crop growth (Chianese *et al*., 2009b). Over the longer term, agricultural biosystems are also capable of holding large stores of carbon (C) mostly in soil organic carbon (SOC) or SOM. The importance of world soils as a source and sink of CO_2 are discussed in Lal (2004) and Lal *et al*. (2007). Conservation tillage, mulch farming, cover crops, and use of manure and compost are some of the practices recommended on the farm for effective SOC sequestration.

Research is ongoing to determine the practices that lead to optimal SOC sequestration to mitigate GHG emissions. Through an analysis of sequestration rates from 67 long-term experiments, West and Post (2002) determined that a change from conventional (CT) to no-till (NT) operations can sequester C, with SOC reaching a new equilibrium in 15–20 years. Baker *et al*. (2007) noted though that the sampling depth in the earlier studies was shallow, typically <30 cm, and may have skewed the results. When using soil sampling techniques that extended deeper into the soil (to 60 cm), NT farming appeared to increase SOC concentrations in the upper layers of some soils but does not appear to store SOC more than plowed till soils over the entire soil profile (Blanco-Canqui and Lal, 2008; Christopher *et al*., 2009). It was concluded that this observation warrants a reexamination of the use of NT methods for storing carbon in soil. Additional studies showed that the rate of SOC sequestration under NT depends on soil type, the quantity and quality of the retained crop residues, and the duration of the NT practice (Mishra *et al*., 2010).

Energy efficiency through implementation of best practices is the one approach being used on dairy farms to reduce energy consumption and therefore CO_2 emissions (Pressman, 2010). Recommendations involve improving lighting, ventilation, installation of refrigeration heat recovery units, new compressors, heat exchangers, and variable speed drives on vacuum systems.

D. Whole farm models to predict GHG mitigation effects

The methods recommended above for mitigation of on-farm GHG emissions in the fluid milk supply chain were obtained from years of research that evaluated the impact of various practices on each GHG. The research was typically conducted on experimental farm plots under a particular farm management system meaning that the data are relevant for that system with a particular soil type, herd size, and climate, for example, and may not apply to a different farm management system. The impact of a particular mitigation procedure for one GHG on another is also relatively unknown as well as the impact of the mitigation on more complex interactions such as the total C and N throughout the farm.

For this reason, process-based whole-farm simulators have been developed. The simulators comprise modules containing semiempirical equations and mechanistic models that account for soil type, crops grown, climate, herd size, manure handling, and other factors for a variety of farms as well as modules that calculate GHG emissions, other types of water and air pollution, and track farm nutrients. The simulators can be used to examine the effects of different manure handling techniques on CH_4 emissions and to determine the implementation costs. Most of the models are continually refined as more experimental data become available.

Farm simulation models are available such as the FarmGHG (Olesen *et al*., 2006; Weiske *et al*., 2006) in Europe; Integrated Farm System Model (IFSM) (Rotz *et al*., 2009) and DairyGHG Model (Rotz *et al*., 2010) in the United States; DairyNZ's Whole Farm Model in New Zealand (Beukes *et al*., 2010), and GAMEDE (Vayssières *et al*., 2009) in France.

VI. MITIGATION STRATEGIES FOR GHG EMISSIONS IN PROCESSING PLANTS

A. Implementation of best practices

Improvements in the energy management of existing U.S. milk processing plants are being made to reduce use of electricity and fuels such as natural gas or fuel oil, and their associated GHG emissions. A recent study (McKinsey & Co, 2009) on the benefits of energy efficiency found that ''energy efficiency offers a vast, low cost energy resource for the U.S. economy.'' Reductions of energy use and utility costs via energy management can be realized on the order of 5% to more than 30% (Doty and Turner, 2009). Energy efficiency best practices are typically implemented following an assessment of current and historical operations, a utility cost analysis, and an energy assessment of plant operations. Understanding historical energy usage and identifying plant major energy using equipment is the first step. Benchmarking of current whole-plant operations and/or system-level operations helps establish priorities of effort and the greatest energy savings opportunities. The utility analysis provides cost-related information necessary to determine economic feasibility of each energy efficiency opportunity. A proper energy assessment includes the above described activities prior to spending much time on the plant floor. A good knowledge of the process and support systems from the point where the milk enters the process to the point where the milk leaves the process is also necessary. Results of the energy assessment will produce a list of potential energy cost reduction projects, such as those that reduce operating time, reduce equipment power requirements, and incorporate new technology or process approaches. Ancillary dairy processing systems include steam, pumping, refrigeration, chilled water, compressed air, lighting, and others. Also, it should be noted that traditional industrial energy assessments are well proven to identify and implement cost reduction measures that are economically feasible, and processing plant GHG emissions are based primarily on fossil fuel-based fuel sources. So, additional or different projects may be identified during the plant assessment that reduce GHG emissions as well.

Examples of tools needed to perform energy assessments include combustion analyzers to determine boiler efficiency, electric power meters, portable data loggers for short-term monitoring, light meters, and temperature sensors. Thermal imaging equipment may be used to identify heat losses throughout the plant and current process controls are inspected for proper operation. Construction of a process flow sheet labeling mass and energy flows throughout the plant can assist with benchmarking current process operations.

Several software tools are available through the U.S. DOE—Energy Efficiency and Renewable Energy Industrial Technologies Best Practices Program (U.S. DOE, 2010) to help processing plants explore techniques for reducing energy costs and lowering GHG emissions. The software includes tools for general plant assessment; motor, pump, and fan assessment; chilled water system assessment; steam assessment; and process heating assessment. Information on federal, local, state, and utility funding incentives for renewable energy and energy efficiency upgrades are found on the Database of State Incentives for Renewables and Efficiency (DSIRE, 2010) and from the U.S. DOE Industrial Assessment Centers (U.S. DOE, IAC, 2010a). Examples of assessments for fluid milk plants (code 311511) are presented describing energy deficits found in plants, potential savings with energy improvements, and costs and payback periods (U.S. DOE, IAC, 2010b). Several Best Practices for decreasing fuel use and electricity use have been published by the dairy industry (Innovation Center for U.S. Dairy, 2009). Bertsch (2005) discussed methodologies for efficient production of steam, electricity, refrigeration and compressed air that were implemented in a milk plant in Germany.

B. Research needs

Energy information data for the fluid milk process as reported by Xu and Flapper (2009) or obtained by energy audit is very useful for establishing benchmark performance of dairy processing plants. However, since the fluid milk process consists of several steps, energy information on each step in the fluid milk process is needed as well to lower the energy costs and GHG emissions associated with pasteurization.

Nicol *et al*. (2005) performed one of the few case studies for determination of the influence of the regeneration step in pasteurization and partial or total homogenization processes on the total energy and specific energy of the whole pasteurization process in an operating fluid milk pasteurization plant. The plant handled 24,000 L/h of milk with a plant run time of 16 h. Energy usage associated with 92% and 95% regeneration, respectively, in the heat recovery heat exchanger or partial (25%) and total homogenization at a pressure of 160 bar and 90% regeneration were compared to a reference or benchmark case with 90% regeneration and total homogenization at a pressure of 130 bar. Total energy was assumed to be the sum of thermal energy at 85% efficiency + chilled water @COP of 2.5 + electricity. (Case studies were also conducted for a skim milk powder plant.) Results showed that specific energy of pasteurized milk production was reduced from the reference case value of 71.5 to 48.7 MJ/kL of milk with a regeneration rate of 95% and to 59.8 MJ/kL with partial homogenization. Homogenization at a pressure of 160 bar resulted in an increase of specific energy to 75.1 MJ/kL. The impact of energy savings on kg CO_{2eq}/gallon of milk was not demonstrated.

While LCA and energy and GHG audits are useful tools for conducting inventories of the effluents and consumption of energy of a milk processing plant, they are not useful for pinpointing the individual processes and interaction of processes that contribute to GHG emissions or for benchmarking of existing milk processes, that is, documenting current operation and economics, or for evaluating the economics and environmental impact of new milk processing concepts proposed to lower GHG emissions (Ramirez *et al.*, 2006; Xu and Flapper, 2009). Process simulation, a computer program that links together mathematical models of each step in a food, chemical, or biochemical processing scheme is a useful tool for this application. Engineers may obtain an estimate of the impact of changes in process variables, such as temperature, made anywhere in the process on changes in the properties of the product leaving any stage of the process, without interrupting the actual process; examine economics associated with retrofitting existing processes with new types of processing equipment; or use process simulation to design new processes. Commercial process simulators are available which are widely used across the chemical processing industries and have rigorous built-in thermodynamic models and unit operations. Currently, if used off the shelf, process simulators are of limited usefulness for simulating food processes or for assessing their environmental impact, but they are potentially customizable upon addition of food physical property data and food process models (Cheng and Friis, 2007). A simulation specific for fluid milk processing and that details GHGs for each processing step and over the entire process will be a useful tool for processors to benchmark their existing processes and useful for investigation of new methods to reduce GHGs.

In a preliminary study, Tomasula *et al.* (2009) simulated the fluid milk process to identify energy usage and GHGs associated with HTST pasteurization and the related unit operations, such as homogenization. Physical property data for milk and cream were provided to the simulator. Packaging was not included as part of the simulation. GHGs were estimated from electrical and natural gas usage over the entire plant through various conversion factors (Calm and Hourahan, 2001; Deru and Torcellini, 2007; ICF, 2009). Pasteurization was found to account for 36% of energy usage, refrigeration requirements accounted for 26%, and CIP procedures accounted for 28% of energy usage. In comparison, Xu and Flapper (2009) reported that fluid milk treatment accounted for 38–48% of total energy used with CIP energy use ranging from 9% to 19% and refrigeration accounting for 2–19% of total energy use. Homogenization and other unit operations accounted for the remaining energy usage. GHG emissions in terms of kg CO_{2eq} were calculated as 2.1 M kg CO_{2eq}/year with approximately 70% of this total associated with electrical use and 30% with natural gas use. This model did not use industry data but the energy usage and GHG results are within those given in U.S. industry estimates. With inclusion of economics, water usage, and unit operations for other milk operations, process simulation will be a useful tool for identifying process improvements and to help reduce the environmental impact of the entire process. In this way, various process simulation scenarios can be compared for their effectiveness in reducing GHGs.

1. Alternative pasteurization technologies

Since a significant portion of fluid milk processing energy and GHG emissions is associated with postpasteurization refrigeration in the plant or in the warehouse, in retail, and in the home, use of alternative pasteurization systems are being considered as possible replacements for HTST pasteurization, such as use of UHT pasteurization of milk (Lewis and Heppell, 2000), as an alternative to HTST pasteurization, which does not require postpasteurization refrigeration. UHT milk is treated at temperatures $\geq$137.8 ºC for $\geq$2 s (FDA, 2009) and is packaged aseptically. It is shelf-stable for about 6 months. Despite its reputation as having a cooked flavor, its production would eliminate the need for refrigerated storage. The reported cooked flavor is attributed to the type of UHT process used (Datta *et al*., 2002). In the indirect heating method, the milk is heated using plate heat exchangers and milk is exposed to temperatures $>$140 °C for $>$2 s, causing loss of vitamins and flavor. In the direct method, a falling film of milk flows through high pressure steam in a chamber and is cooled at the bottom of the chamber. The flavor is preserved because the milk is heated and then cooled instantly. In pilot – scale studies, Chandarana *et al*. (1984) reported that the UHT process consumes additional energy relative to HTST pasteurization but net energy savings are realized because the product does not require postprocessing refrigeration. Capital costs for replacement of HTST equipment and other modifications associated with installation of UHT equipment may be significant because of the increased production capacity that would be required for replacement of HTST pasteurization in the United States. Frey *et al*. (1980) estimated that use of UHT could save 12M barrels of oil annually. The feasibility of integration of alternate energy management systems to support UHT processing also needs to be investigated.

Decreases in energy usage, GHG emissions, as well as water, associated with fluid milk processing, may be possible through the use of alternative milk pasteurization technologies (nonthermal techniques), often thought of as the next generation in pasteurization. Some of the technologies may also have potential for CIP operations or wastewater treatment. The influence of the techniques on energy usage and GHG emissions can be compared to base cases for HTST pasteurization, or examined through process simulation to evaluate and optimize the particular alternative technology. Some of the techniques may be used alone or in combination with HTST pasteurization to treat milk. Alternative pasteurization technologies such as high pressure homogenization (HPH) (Diels and Michiels, 2006; Diels *et al*., 2005; Pereda *et al*., 2007; Roach and Harte, 2008), pulsed electric field technology (PEF) (Bendicho *et al*., 2002; Devlieghere *et al*., 2004; Evrendilek *et al*., 2001; Sepulveda *et al*., 2005; Toepfl *et al*., 2006), ultrasound (Bermudez-Aguirre *et al*., 2009; D'Amico *et al*., 2006; Knorr *et al*., 2004; Villamiel and Jong, 2000a,b), ultraviolet (UV) light (Matak *et al*., 2005; Milly *et al*., 2007; Reinemann *et al*., 2006), cold microfiltration with CO_2 (Fritsch and Moraru, 2007) or microfiltration (Hoffman *et al*., 2006; Kulozik, 2007), bactofugation (Giffel and Horst, 2004; Wieking, 2004), infrared heat treatment (Krishnamurthy *et al*., 2008), and CO_2 (Garcia-Gonzalez *et al*., 2007; Hotchkiss and Lee, 1996; Hotchkiss *et al*., 1999; 2006; Ruas Madiedo *et al*., 1996) have not yet been evaluated for pasteurization of milk in a whole process scenario which would indicate their usefulness for lowering energy use and GHG emissions. The energy efficiency of some of these processes in general is described in Wang (2009). PEF and ultrasound (Sampedro *et al*., 2005; Soliva-Fortuny *et al*., 2009; Villamiel and Jong, 2000a,b) act by affecting cell membranes, denaturing enzymes, or changing oxidation and reduction reactions in cells with little increase in temperature. HPH (Datta *et al*., 2005) disrupts microbial cells; bactofugation is essentially a centrifugation method; and, microfiltration relies on a membrane that allows skim milk to pass through while retaining most bacterial vegetative cells, spores and somatic cells. With the exception of bactofugation and HPH, most of these methods require that the cream be processed separately and added back to the milk, which can pose a challenge for integrating into fluid milk lines which pasteurize milk at a designated fat level. Little information is available on the electrical energy usage associated with nonthermal technologies. Juriaanse (1999) compared the energy consumption of various milk pasteurization and sterilization technologies. The energy consumptions reported in 10^6 kWh/year were pasteurization (13), microfiltration (18), UHT (73), sterilization (166), and pulsed electric field (7). Toepfl *et al*.

(2006), though, reported that the use of PEF for microbial inactivation in pasteurization requires up to 1000 kJ/kg of milk, which exceeds that for HTST pasteurization, but can be substantially reduced to the energy used for thermal pasteurization, 20 kJ/kg, if PEF is performed at an elevated temperature such as at 50 °C, and use is made of the synergistic heat effects of the PEF treatment with heat recovery through a regeneration system of 95%. Even though the energy intensity is the same there may be a difference in the GHG emissions depending if the energy source is provided by natural gas or electricity. The inclusion of alternative technology models into a process simulation of the base milk plants would provide a useful tool to manufacturers who seek guidance and insight on including these newer processes into their plants and will allow them to calculate energy requirements and the environmental impact of these processes.

Sustainability has a number of dimensions that include human health, energy, GHG emissions, community, waste and natural resources (Innovation Center for U.S. Dairy, 2008). Tools such as process simulators used in efforts to evaluate the sustainability of a process in terms of the GHG emissions and energy should also help understand the impact of system changes on human health (EPA, 2007). A food process simulator, targeting potato and vegetable processing, was developed previously (Kozempel *et al.* 1995; Tomasula *et al.*, 1990, 1991) which in addition to including models for the unit operations included information on changes in the nutrition and quality of potatoes at the various steps of processing, for example, levels of vitamins and minerals, as well as the degree of browning or texture. Nutritional and quality information for milk if included in process simulation would help processors balance changes in these quantities with type of pasteurization technique, HTST, UHT, or alternative, and their supporting unit operations such as homogenization and the environmental impact of their processes. Ample references are available for the effects of HTST pasteurization on milk nutrition. Much information is available on the thermal impact of UHT pasteurization on milk quality with specific focus on the whey proteins (Douglas *et al*., 1981; Farrell and Douglas, 1983; Lewis and Heppell, 2000) as well as the influence of direct or indirect UHT processing on the whey proteins and milk quality (Tran *et al*., 2008). Information on the effects of the various alternative processes on the nutrition and quality of milk are scarce since most of the technologies are of recent development. Interestingly, UV treatment of milk has been reported to increase the vitamin D content of milk from <1 to as high as 31 μg/L (Burton, 1951) but may also result in milk having oxidized flavors. HPH treatment of milk disrupts the various electrostatic and hydrophobic interactions (Adapa *et al*., 1997; Hayes *et al*., 2005) and also can modify casein micelles (Roach and Harte, 2008). Research is needed to determine the appropriate quality and nutritional indicators in process simulation of each unit operation encountered in fluid milk processing.

2. Alternative CIP procedures

CIP procedures account for 9–25% of total energy used in milk plants (Xu and Flapper, 2009). The U.S. dairy industry estimates that current high temperature CIP systems use more than half of a processing plant's energy. CIP processes are conducted to err on the side of product safety, that is, the pasteurization and auxiliary equipment may be flushed for longer than necessary and may use larger volumes of flushing solutions and temperatures that are higher than necessary. Through eliminating dead zones in processing equipment and advanced monitoring techniques (Alvarez *et al*., 2010; Van Asselt *et al*., 2002) significant reduction of the cleaning sequence, wastewater volume, and detergent volumes was demonstrated while maintaining sanitary concerns. Eide *et al*. (2003) showed that CIP methods using smaller volumes and lower temperatures, such as enzyme-based cleaning and one-phase alkaline cleaning, or the use of membrane filtration for reuse of detergents, were the best alternatives to conventional CIP by reducing energy use. Graßhoff (2002) demonstrated the environmental effectiveness of enzyme-based CIP processing but noted that the enzyme dosage, process control of the system, and economics of using enzyme cleaners still need to be addressed.

In addition to the methods above, electrolyzed oxidizing water (EOW; Huang *et al*., 2008) has future potential applications for CIP applications to lower energy use and GHG emissions. EOW is produced by separating a weak sodium chloride solution into alkaline and acid components. Walker *et al*. (2005a,b) demonstrated that small pieces of materials used in milking systems and soiled with milk inoculated with bacteria could be cleaned at 60 °C and lower temperatures. They suggested that EOW has the potential for use as a cleaning and disinfecting agent for milking systems. In tests with inoculated apple juice on stainless steel chips, EOW eliminated inoculated bacteria but process parameters such as timing, flow velocity and temperature still need to be established. The EOW system promises to be economical, easy to handle and have low hazard risk (Amaratunga *et al*., 2007).

The recent addition of criteria for continuous water disinfection using UV light as described in the Pasteurized Milk Ordinance (FDA, 2009) also may lead to the develop of systems for CIP based on UV light and other so-called nonthermal methods described earlier.

3. Alternative energy management systems

The dairy industry is committed to reducing GHG emissions across the fluid milk processing chain by 25% by the year 2020, and this can only be accomplished in the fluid milk process plant through use of alternative energy management systems or through the use of alternative energy technologies, or both. Process simulation has great potential as a tool for whole process benchmarking as discussed above. The resulting benchmarked or base cases for milk processing for a variety of plant sizes and at various locations in the United States can then be used to explore the use of alternative energy management systems to replace electrical or natural gas sources of energy. However, alternative energy management systems cannot be simply exchanged with the current electrical and natural gas systems of a plant. Optimization of existing equipment may also be necessary or the alternative source may only be useful for a portion of a plant's energy needs. Schnitzer *et al*. (2007) reported that for milk processing plants in Austria, the heat demand of HTST pasteurization would require enlarged heat exchanger capacity if solar energy were used, but solar energy would be appropriate for CIP systems. Processes benchmarked through simulation would allow determination of the feasibility of integration of solar energy and other energy systems such as co-generation, heat pumps, geothermal energy and wind energy, for example, to supply process heat and electricity and optimization of plant operations required to accommodate them if necessary.

There are very few examples in the literature of integration of alternative energy management systems into milk or dairy processing plants or into any industrial plants for that matter. However, due to financial incentives offered by states and the federal government, installations of solar photovoltaic technologies are increasing to supply some of the electrical requirements at food-processing plants.

Atkins *et al*. (2010) discussed the use of pinch technology for integration of solar thermal in the relatively low temperature food, beverage and textile sectors. The method was demonstrated for a New Zealand milk powder plant. Including solar thermal requires analysis of climactic conditions throughout the year and can present a challenge in design due to the continuous nature of the demand for power and the variable solar supply. Anderson and Duke (2007) analyzed four types of solar collectors and found that a (University of Waikato) building-integrated solar collector could contribute significantly to energy use in dairies in New Zealand.

Ozyurt *et al*. (2004) compared the energy consumed to pasteurize 1 kg of milk of two conventional milk pasteurization systems to a liquid–liquid vapor compression heat pump. It was determined that the heat pump system would save 66% in primary energy compared to the conventional milk pasteurization systems. A plate pasteurizer consumed 1.9 times the energy of the heat pump. Hanneman and Robertson (2005) presented several case studies of how heat recovered through heat pumps and heat engines could be used to recover heat in steam condensate systems, in the generation of compressed air, to save energy in CIP, and in milk, cream, and cheese processing.

Tynan (2005) reported on a case study of a CHP (combined heat and power) system installed at a dairy facility in Ireland. The CHP system generates electricity and uses the generated heat to provide steam. The overall efficiency of the process is 58%. Reported energy savings were \$1.7M euros/year with reduction of 27,920 tons of CO_2.

4. Packaging

The U.S. dairy industry estimated that the GHG emissions in the milk packaging sector are due to raw material production (65%) and to container formation (35%). To reduce emissions, the U.S. dairy industry recommended that the energy efficiency of blow molding and container forming operations should be increased, the amount of material used in packaging should be reduced, and more recycled materials should be included in the plastic packaging. Increased recycling of the packaging by the consumer is also important. In their study, Cashman *et al*. (2009) assumed that all 1/2 gallon plastic-coated paperboard and 1 gallon HDPE bottles were land-filled, recycling was not considered.

The availability of publications related to packaging of milk is very limited. An LCA on packaging of milk (Keoleian and Spitzley, 1999) suggested that refillable HDPE and polycarbonate containers and the flexible pouch (aseptic packaging) were environmentally preferable with respect to life cycle energy and waste generation. However, the market may not favor the refillable HDPE since the containers would have to be returned to the point of purchase. Storage space for the empty containers and special handling and possibly deposit fees would be necessary to encourage returns. The pouch is used in some areas of the United States but the resealability and puncture resistance for the pouch limits market penetration and consumer acceptance is low.

Manufacturers have decreased the amount of plastics used in the HDPE bottle, and their weight, through redesign. Also, if the bottles are lighter, shipping and fuel costs, as well as GHG emissions decrease as well. Lighter caps are being used by some manufacturers and removing the handle on the milk jugs has been proposed to decrease the weight of the bottle which would also lower transportation costs.

Franklin Associates (2010) completed an LCA to compare the total energy requirements, energy sources, air and water pollutants, and solid waste from the production of recycled HDPE resin and PET (polyethylene terephthalate), used in some milk packaging, from recycled plastic to that of virgin polymer. Recycled HDPE resin required 71 trillion BTU less energy to process than the equivalent in weight of virgin HDPE. The reported savings in GHG emissions was 2.1 M tons CO_{2eq}.

Manufacture of milk containers using postconsumer HDPE has the potential to significantly lower the GHG emissions and energy due to the raw materials in packaging material as well as for secondary packaging and possibly meet the industry goal of a 25% overall CO_{2eq} reduction.

5. Mitigation strategies in transportation

To decrease diesel fuel use and the associated GHG emissions, optimization of delivery of products to the cold storage sites, distribution centers and retailers needs to be examined to reduce the number of miles traveled and help drivers improve their efficiency. The use of biodiesel fuels needs to be considered as well. Programs such as the U.S. EPA Certified SmartWay Tractor and the U.S. EPA Certified SmartWay Trailer have been initiated to help reduce GHG emissions. The use of renewable fuels, such as biodiesel, reduces reliance on imported energy. The Energy Independence and Security Act of 2007 (EISA) established categories for renewable fuels and the eligibility requirements. The EPA (2009b) published draft GHG emissions for the various biofuels that will meet the mandates of EISA. Similarly, use of low GWP refrigerants and system designs with low refrigerant charge are needed for low GHG emission rate distribution fleets.

VII. CONCLUSIONS AND FUTURE PROSPECTS

The analysis of GHG emissions using LCA methods has established the baseline GHG emissions in each sector of the fluid milk supply chain, from crop production to retail. The LCA may be used as a guide to identify the best practices and develop research initiatives to target the sectors that have the largest impact on the environment. LCAs conducted in the United States and other milk-producing countries have shown that feed production, manure management, and enteric CH_4 have the largest impact on GHG emissions. Even though the GHG emissions from the off-farm sectors are far less, it is in these sectors that energy use in the form of fossil fuels, both domestic and imported, is greater, and initiatives that reduce energy use will not only contribute to decreases in the overall GHG emissions of the fluid milk chain but will reduce reliance on imported fuels.

LCA as a tool can only provide a baseline for current GHG emissions; it cannot be used to predict the impact of an improvement to lower GHG emissions on milk quality or production levels, on other sectors of the milk supply chain, or on the other impact categories, such as water quality. In this case, scientific and technological knowledge along with significant practical user input is required. Much of this knowledge can be embodied in farm or process simulators that have the potential to allow assessment of the environmental and economic outcomes of the improvement on other sectors in the fluid milk supply chain.

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