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Greenhouse gas emission analysis for USA fluid milk processing plants: Processing, packaging, and distribution

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ABSTRACT

A gate-to-gate life cycle assessment was conducted to evaluate the Global Warming Potential associated with USA fluid milk processing. Data collected from 50 fluid milk processing plants were used to construct a life cycle assessment model for the greenhouse gas (GHG) emissions across the milk processing system, from raw milk entering the plant's refrigerated storage silo through delivery of packaged fluid milk to retail store's loading dock. Carbon dioxide equivalent (CO_2e) emissions associated with the processing, packaging, and distribution in the processing of packaged fluid milk were investigated. Upstream emissions associated with raw materials, extraction, and transportation were included. Average GHG emissions for processing, packaging and distribution were 0.077, 0.054 and 0.072 kg CO_2e kg^{-1} packaged fluid milk, respectively. Overall GHG emissions were 0.203 (±0.017) kg CO_2e kg^{-1} packaged fluid milk with major individual GHG contributors being plant electricity usage (27% of total) and truck fleet tailpipe emissions (29% of total).

1. Introduction

In 2009, USA fluid milk per capita consumption was 71 kg (USDA ERS, 2010). Thermal processing of milk is a multi-step, energy intensive process that is used to transform raw milk into various types of dairy products – skim milk, 1% milk, 2% milk, whole milk, cream, cheese, whey and others. In 2005, the production of raw milk and cheese was 645 million metric tons globally (Xu & Flapper, 2009). In comparison with the European dairy producing countries, the USA processes much more raw milk into consumable fluid milk, annually amounting to 25×10^9 kg (International Dairy Foods Association, 2007). The USA is followed by Great Britain at 8.5×10^9 kg and the Netherlands at 2.2×10^9 kg per year (Xu & Flapper, 2009). Total USA production of raw milk in 2009 was over 85×10^9 kg (USDA NASS, 2009).

The production and processing of fluid milk requires numerous resource inputs and environmental outputs (Eide, 2002) that contribute to greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC, 2006), the risk of catastrophic climate effects is increasing from anthropogenic releases of GHG. Gases such as carbon dioxide (CO_2), methane (CH_4), and selected refrigerants are GHGs that trap heat within the atmosphere. Scientific consensus on global warming, along with the fear of detrimental climate change is leading to increased effort to develop new technologies in attempt to mitigate global warming.

Life cycle assessments (LCAs) have been used to study milk production, packaging, and processing as a tool for integral assessment of the environmental sustainability for products or processes by including all phases of the life cycle (Cederberg & Mattsson, 2000; Gerber, Vellinga, Opio, Henderson, & Steinfeld, 2010; Guinard, Verones, Loerincik, & Jolliet, 2009; Heller & Keoleian, 2011; Hospido, Moreira, & Feijoo, 2003; Keoleian, Phipps, Dritz, & Brachfield, 2004; Ross & Evans, 2002; Sonesson & Berlin, 2003; Thomassen, van Calker, Smits, Iepema, & de Boer, 2008). LCAs provide quantitative, confirmable, and manageable models to evaluate production processes, analyze options for innovation, and improve understanding of the complexity in systems. LCAs are also an internationally accepted method for the identification of an element that has a high contribution to the environmental burden of a product (Guinee, Heijungs, & Huppes, 2004; Halberg, vad der Werf, Basset-Mens, Dalgaard, & de Boer, 2005). The LCA methodology used in this study was based on ISO 14044 standards (ISO, 2006a, 2006b). The purpose of this study was to better understand the GHG emissions from USA milk processing via LCA and use the results to inform strategic decision making by the USA dairy industry in their ongoing mitigation efforts.

A carbon footprint is a measure of the overall amount of carbon dioxide and other GHG emissions associated with a delivery of

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a product or service (EPLAC, 2007). The carbon footprint is quantified through the Global Warming Potential (GWP) expressed in terms of an ‘equivalent’ amount of carbon dioxide (i.e., CO_2e) released into the atmosphere (through the production and distribution of a product or service). As defined by the Intergovernmental Panel on Climate Change (IPCC, 2006), a GWP is an indicator that reflects the relative effect of a GHG in terms of climate change considering a fixed time period, such as 100 years (GWP_{100}). The 100 year GWPs developed by the IPCC (2006) are used in this study (e.g., CO_2: 1, CH_4: 25, and N_2O: 298).

The work reported was part of a larger effort to evaluate the entire cradle-to-grave GHG emissions associated with fluid milk consumption in the United States of America. Companion papers describing the remaining unit processes are being published in this special issue. This paper presents a GWP analysis for impacts associated with fluid milk processing plants. In particular, carbon dioxide equivalent emissions for processing, packaging, and distribution in the delivery of a kg of packaged fluid milk to the retail store’s loading dock were investigated. In addition, whole plant electrical and fuel energy intensities are presented. In the context GHG emissions shown, processing refers to the thermal processing and clarification of raw milk, including container filling. There are three components to processing GHG emissions: plant electricity, plant heating fuel (generally natural gas) and milk refrigeration system refrigerant loss. Packaging is focused on the evaluation of the emissions associated with the manufacture of packaging materials for processed milk containers. There are two components to packaging GHG emissions: packaging materials and electricity consumption for package formation. Distribution is focused on the evaluation of the tailpipe and refrigerant emissions associated with the transportation of processed and packaged fluid milk from the plant to the retailer’s point of delivery. The main objectives for this gate-to-gate (i.e., entering the processor through delivery to customer’s loading dock) LCA were to assess the sources of GHG emissions across the specific dairy unit processes, to compute the life cycle inventories, to evaluate the environmental impact metric (kg CO_2e kg^{-1} milk), and to identify the areas of greatest sustainability impact.

2. Materials and methods

2.1. Functional unit and system boundaries

The functional unit was defined as a kg of packaged fluid milk delivered to the plant’s customers. The comparative environmental impact metric was defined as carbon dioxide equivalent per kg of packaged fluid milk. The system boundaries (see Fig. 1) begin with the raw milk entering the plant’s refrigerated storage silos and end with delivery of packaged milk to the retailer via the plant’s distribution truck fleet. The management of postconsumer waste was not included because the project scope ends at the retail customer’s loading dock. Incidental effects such as employees’ commutes and business travel for industry executives were not included.

In determining whether to include specific inputs, a cut off criteria was established as 1% threshold for mass and energy. Exceptions to this exclusion were made in cases where significant environmental impact was associated with a small mass input. Where allocations of inputs were required, the allocation procedures followed the ISO allocation hierarchy (ISO, 2006a, 2006b). Primary allocations, discussed further in a later section, occurred for excess cream production and processing plant energy use (electricity and plant heating fuel) based on the fraction of total packaged milk to total processed plant fluids (which could include juices, teas, or other products). Packaging and distribution were not allocated because the reported total in the survey were specific to packaged milk.

2.2. Life cycle inventory data

Starting in mid-February 2008, a survey was sent to eight milk processing companies that requested a variety of operating and material consumption data for the calendar year 2007. Surveys were returned from 50 individual fluid milk processing plants. Information requested from each plant included:

a) plant energy consumption – electricity, natural gas, #2 fuel oil, propane, diesel, and gasoline;
b) water consumption –both the amount of plant/process water and on-site waste water treatment;
c) truck fleet fuel consumption – either the amount and type of fuel used to deliver packaged fluid milk to retail or the total miles driven by the fleet. It was found that operating plants either owned and operated the fleet or contracted through a second party trucking company;
d) refrigerant purchases for both the plant and truck fleet – amount and refrigerant type(s);
e) description of all on-site milk packaging equipment and production rates;

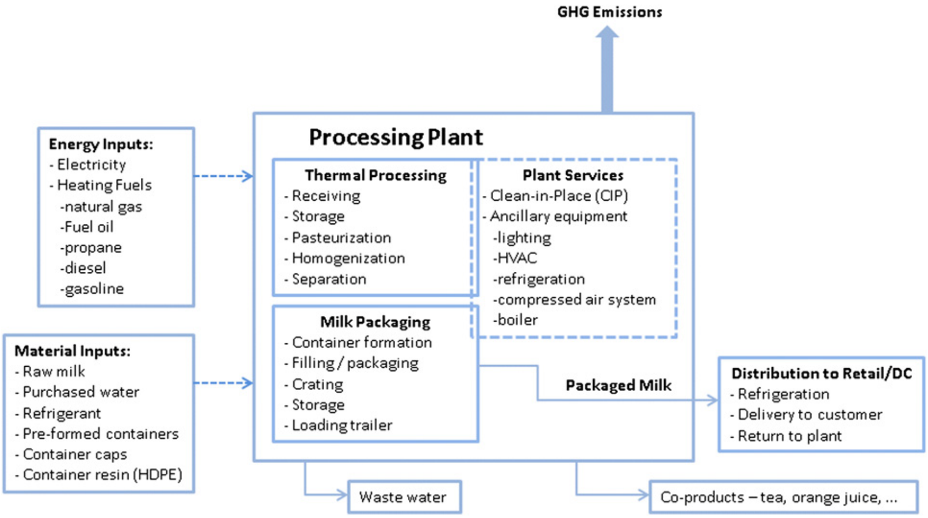

Fig. 1. Input and output flow diagram for fluid milk processing, packaging, and distribution.

f) packaged milk type and container format and sizes, such as gallon or half-gallon high density polyethylene (HDPE) or half-pint paperboard; and
g) total plant processed amounts for total plant fluid, fluid milk, and packaged milk (by container type).

Information provided in the surveys along with additional correspondence for clarification and verification purposes were the primary data sources for the study. Fig. 1 shows the unit processes considered with the various inputs and outputs. The majority of data were provided by the processing plants and their supply chain service providers. When not available from primary sources, data for some of the inputs/outputs were derived from equipment manufacturer's technical specifications or product literature (e.g., blow molding equipment), from NREL's US Life Cycle Inventory database (NREL, n.d.), from the European ecoinvent database (SCLCI, 2010), from existing manufacturers' LCAs, and from other industry provided data sets. For example, we have had numerous discussions with a major manufacturer of the large majority of blow molding equipment used in USA milk processing regarding the energy use of these machines as a function of capacity – including power requirements for the extruder, chilled water, compressed air, and grinding of waste plastic for reuse.

2.3. Data uncertainty and reconciliation

Knowledge uncertainty reflects limits of what is known about a given parameter, while process uncertainty reflects the inherent variability within the reported carbon footprint for the industry. It should be noted that the data provided by each plant were considered exact (i.e., without uncertainty in a classical sense), thus did not contribute directly to error bounds in the final result. This approach was chosen because plant level information was linked and using Monte Carlo simulation with random variable selection for coupled parameters would introduce artificial variation in the final results. So, statistical methods and Monte Carlo simulation were used to address uncertainty and ranges of emission factor data. Where information on the range of individual emission factors was available (e.g., kg CO_2e kg^{-1} diesel), this range was used to define a normal probability density function (PDF) describing the expected variation. For other parameters, a normal PDF with a relative standard deviation (RSD) of 10% was used. However, some parameters, such as the mass of low-density polyethylene (LDPE) container's cap, were small enough that an RSD of 10% would result in negative values. A lognormal PDF was used for these situations. Data reconciliation included an evaluation of appropriate survey values and units, the identification of potential data outliers, and matching fluid milk processing with the number and size of reported packages. Data from all of the plants were transformed to a uniform format and units.

2.4. Emission factors

2.4.1. Electricity

When the location of electricity consumption was known, e.g., at the plant itself, this study used emission factors (in kg CO_2e kWh^{-1}) for the appropriate major USA regional interconnection grids. The source energy emission factors per unit of delivered electricity for each of the three regions are provided in Table 1 (Deru & Torcellini, 2007). National average emission factors were used when the location was unknown, specifically for estimation of the GHG emissions associated with off-site HDPE container formation.

These three main regional grids were chosen rather than national, state, or utility-level emission factors because there are limited interactions or energy transfers between them. The three regions are Eastern Interconnection, Western Interconnection, and the Electric Reliability Council of Texas (ERCOT) Interconnection (Fig. 2; NERC, 2012). To fully account for emissions associated with electricity use, an analysis must include not only the on-site consumption, but also the 'pre-combustion' effects and the 'transmission and distribution' (T&D) losses. Pre-combustion effects include the energy usage required to extract, process, and deliver the primary fuels to the power plant. T&D losses are the energy losses post generation and associated with delivery and transmission to the point of use.

Table 1
Emission factors used to compute GHG emissions from electricity use within each USA region.[a]

Electricity regions	Included transmission and distribution losses (%)	Combined pre-combustion, transmission and distribution losses emission factors (kg CO_2e kWh^{-1})
Eastern	9.6	0.888
Western	8.4	0.669
ERCOT	16.1	0.960
National	9.9	0.836

[a] Data from Deru and Torcellini (2007) and SCLCI (2010). The unit processes from the ecoinvent database for the three interconnections were used to model emissions associated with electricity consumption. In the ecoinvent database, specific fuel mixes were prepared for each of the 8 North American Electric Reliability Council regions, and these have been combined to create Eastern, Western, and Electric Reliability Council of Texas (ERCOT) unit processes.

2.4.2. Plant fuel energy

Fuel energy emission factors for pre-combustion and on-site combustion were also used in the study and derived from the US LCI database (see Table 2). The pre-combustion emission factors (in kg CO_2e $unit^{-1}$ fuel) include factors related to energy used to extract, process, and deliver the fuel to the point of use. The majority of fuel energy in milk processing comes from natural gas and is used to produce steam for thermal processing, equipment cleaning and other plant processes.

2.4.3. Truck fleet tailpipe emissions

Each plant reported either total distance driven to deliver milk or total volume of diesel purchased to deliver milk after processing and packaging. From 1990 to 2005, the gas mileage for heavy trucks has been estimated at 2.21–2.47 km L^{-1} (Davis, Diegel, & Boundy, 2008) and, from 1992 to 2002, 2.38–2.59 km L^{-1} (US Census Bureau, 2004). A truck fuel efficiency of 2.42 km L^{-1} was used, based on heavy class 8 trucks to convert total distance driven to fuel usage. A combined emission factor of 10.4 kg CO_2e kg^{-1} diesel from direct combustion (Davis & Diegel, 2007) plus an additional 20% to account for well-to-tank emissions (NREL, n.d.), totaling 12.5 kg CO_2e kg^{-1} diesel, was used to compute truck tailpipe GHG emission. The source for well-to-tank emissions lists a range of 15–25%, so an average value of 20% was selected and used. Combining fuel efficiency and pre-combustion burdens, the tailpipe emissions were estimated to be 1.55 kg CO_2e km^{-1}.

2.4.4. Truck and plant refrigerant loss

Plants reported the amount and type of refrigerant purchased for both their truck fleet and plant refrigeration systems, which were assumed to be equal to the amount lost to the environment due to leakage (i.e., 'sales-based approach'; GHG Protocol, 2005). Total emission release was determined by using the refrigerant's GWP (Calm & Hourahan, 2001) plus the GHG emissions associated with the manufacture of the refrigerant (6.65 kg CO_2e kg^{-1}, based on the ecoinvent value for R-134a; SCLCI, 2010), assumed to represent all refrigerants except for ammonia since it is very small

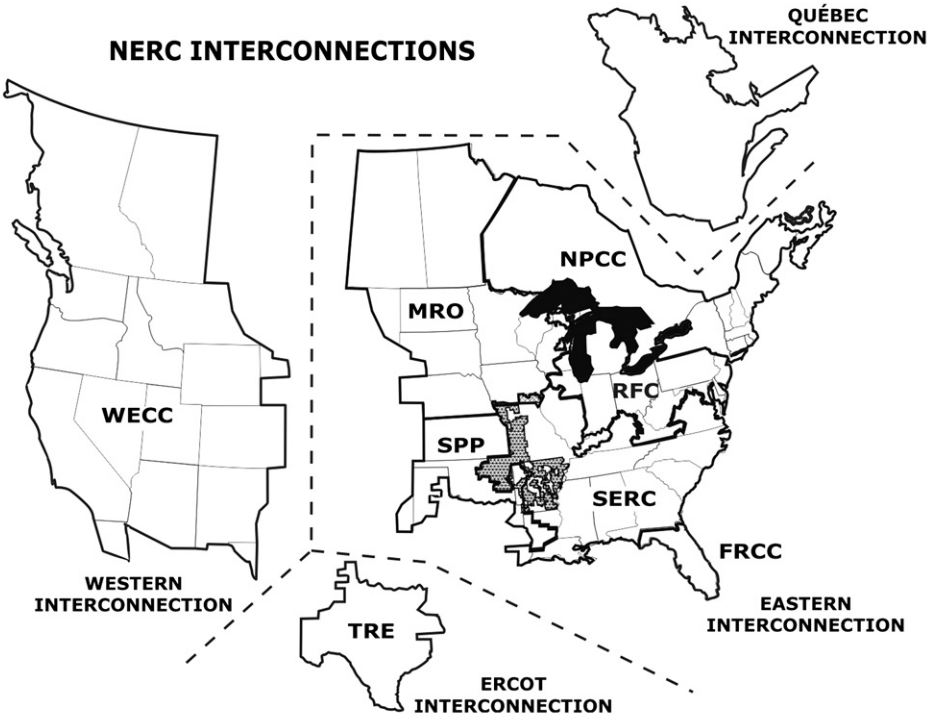

Fig. 2. Three North American Electric Reliability Council regional electrical grid interconnections (NERC, 2012).

compared with the direct GWP of each refrigerant. The upstream GHG emission for ammonia production (1.7 kg CO_2e kg^{-1} NH_3; EFMA, 2000) was included.

2.4.5. Packaging materials

Three general types of fluid milk containers [HDPE, polyethylene terephthalate (PET) and paperboard carton] of various sizes were reported by each plant. Most plants purchased HDPE resin to blow mold their own large volume bottles on-site (3.79 L and 1.89 L jugs), while other sizes were purchased as pre-formed containers. For on-site blow molding, a portion of the reported whole plant electricity was allocated to the packaging process from a model of power requirements for the extruder, chilled water, compressed air, and grinding of waste plastic for on-site reuse. Specific information from major USA manufacturers of the blow molding equipment was used to determine the energy requirements for production (e.g., blow molding) and filling of the packages. If processors did not purchase resin, it was assumed that pre-formed containers were purchased from an outside supplier. Most processors purchased PET bottles and paperboard carton blanks from a specialty manufacturer. Total packaging emissions included container material (i.e., raw material extraction, transport, and manufacture), container formation, and caps. Table 3 shows industrial standard GHG emission factors of each packaging raw material type. The emission factors were estimated from ecoinvent (SCLCI, 2010).

A number of inputs did not meet the 1% threshold requirement. These included: the estimated distance of 250 miles (402 km) that the resin traveled to each plant, bottle labels, pallets, secondary packaging/wrapping, and milk crates. The majority of milk crates are recycled for their HDPE content, resulting in minimal net emissions. Other assumptions for packaging calculations included: emissions from single-serve HDPE bottles were linearly scaled from the 8 ounce size, large LDPE bags were linearly scaled from 1 gallon size (3.79 L); quart (0.946 L) PET white bottles were assumed similar to quart clear; paperboard cartons are formed, filled and sealed at the plant. If not designated, paperboard containers were assumed to be four ounces (0.118 L). Processing plant infrastructure was estimated to contribute approximately 0.8% of the GHG emissions for the combined stages of processing, packaging, and distribution. This was based on an economic input output analysis (Green Design Institute, 2012) of the overall GHG burden was performed for a large fluid milk plant (Dalton, Criner, & Halloran, 2002) valued at 33.6 million US dollars capable of producing 2.27 million L each week and was compared with the burden associated with producing milk. The analysis was based on a plant

Table 2
Emission factors used to compute GHG emissions from on-site fuel energy use.[a]

On-site fuel (units)	CO_2e emission factors (kg CO_2e $unit^{-1}$)		
	Pre-combustion	Combustion	Combined pre-combustion and combustion
Diesel (L)	0.549	2.732	3.281
Fuel oil (L)	0.536	3.178	3.714
Natural gas (m^3)	0.442	1.957	2.399
Propane (L)	0.306	1.617	1.923

[a] Data from Deru and Torcellini (2007).

Table 3
Standard emission factors used to compute GHG emissions for the listed raw materials.[a]

Material type	From cradle to 1 kg raw material (kg CO_2e kg^{-1} material)
HDPE	1.920
LDPE	2.100
LLDPE	1.840
PET	2.750
Paperboard carton	−0.254

[a] Data from SCLCI (2010). Ecoinvent database values of upstream raw material extraction and energy requirements were used for each container material type. Note that biogenic carbon was considered neutral with respect to GHG emissions.

life expectancy of 50 years and a retail milk cost of 0.793 US dollars per liter. The retail value was adjusted for contractor markups and taxes. In addition, the GHG burden from five million US dollars worth of distribution trucks was added to the plant infrastructure. This confirmed that the expected impact of processing-related infrastructure is small, compared with the operational burden, due to the large annual processing volume and long life of existing plants.

2.5. *Co-product allocation*

There was a need to account for two types of co-products in this portion of the life cycle study – cream and packaged non-fluid milk products. The cream allocation allowed the milk fat burden to be appropriately distributed among the various milk fat products. Raw milk is delivered to the processing plant, stored in refrigerated tanks, and then enters the pasteurization process. It is during this step that the cream, at around 40% fat content, is separated from the fluid milk stream. Depending on the desired fat content of the packaged milk (i.e., whole, 2%, 1%, etc.) a portion of the cream is mixed back into the fluid milk. Excess cream is stored in a refrigerated tank and typically transported from the facility to produce ice cream, butter, and other products. The proportion of the incoming milk burden that is attributed to the excess cream was removed from the fluid milk value chain at this point. The second allocation was for packaged fluids other than fluid milk. Plants produce products such as orange juice, apple juice, tea, and others. Some are pasteurized and others, such as tea, are heated to temperatures near those of high-temperature short-time (HTST) thermal processing. Therefore, the allocation for these products was on a volumetric basis, with the assumption that the energy requirements for the products were similar.

3. Results and discussion

3.1. *GHG emissions by unit process*

Average results of GHG emissions associated with each unit process in 2007 are provided in Table 4. All major emission sources spanning from raw milk entering the refrigerated storage silo to delivery of packaged fluid milk to the retailer are included. Processing facility emissions were grouped into three major categories: purchased electricity, on-site fuel combustion, and refrigerant loss. Packaging-related emissions were grouped into two categories: raw material manufacture and container formation. Distribution emissions were grouped into two categories: mobile fuel combustion and refrigerant loss.

Table 4
Summary of GHG emissions results for each unit process.

Unit process	GHG emissions[a] (kg CO_2e kg^{-1} packaged milk)
Processing	
Purchased energy	0.054 (±0.0090)
On site fuel combustion	0.022 (±0.0044)
Refrigerant loss	0.001 (±0.0014)
Total	0.077 (±0.0109)
Packaging	
Raw material	0.034 (±0.0034)
Container formation	0.020 (±0.0012)
Total	0.054 (±0.0044)
Distribution	
Mobile fuel combustion	0.058 (±0.0091)
Refrigerant loss	0.014 (±0.0037)
Total	0.072 (±0.0102)
Overall total	0.203 (±0.0174)

[a] Numbers in parentheses indicate 95% confidence interval of mean.

Over the full fluid milk gate-to-gate life cycle, 0.203 (±0.017) kg CO_2e kg^{-1} of packaged fluid milk was emitted. As shown in Fig. 3, the largest single emission was from mobile fuel combustion (i.e., truck fleet tailpipe emissions) which contributed 0.058 (±0.009) kg CO_2e kg^{-1} of packaged fluid milk or 28.8% of total. The next largest was found to be the processor's purchased electricity which contributed an average of 0.054 (±0.009) kg CO_2e kg^{-1} of packaged fluid milk or 26.5% of the total system GHG emissions. The other large individual GHG contributor to the system was found to be the packaging raw material, which account for 16.8% of total emissions. The plant fuel, generally natural gas, is a less significant contributor (10.9% of total emissions) because natural gas is a cleaner energy source and fluid milk processing plants utilize waste-heat recovery systems within the pasteurization process. Again viewing Fig. 3, relative average plant GHG emissions contributions by percentage can be seen.

3.1.1. *Processing emissions*

Whole plant electrical and fuel energy consumption was reported for the fluid milk processing plants and statistical data are shown in Figs. 4 and 5 as a function of the plant's packaged milk output. Data shown are whole plant site-energy intensities, and as stated by Xu and Flapper (2009, 2011), more data are needed to better benchmark and identify/implement energy efficiency measures in fluid milk plants. In terms of GHG emissions, this study found that the electricity and fuel usage represented 70.1% and 28.6% of total processing emissions, respectively. Electricity at the processing stage includes all electricity used at the plant except that allocated to container formation, including all overhead consumption such as for refrigeration, compressed air, heating, ventilating, and air-conditioning (HVAC), lighting, and office equipment. Fig. 6 shows the total processing-related emissions for the calendar year of 2007. It can be seen that emissions for the plants with milk production rates below 80 million kg y^{-1} are much more tightly clustered than for annual packaged milk production greater than 80 million kg y^{-1}. The variation in processing can be explained by several reasons: the difference in electricity emission factors due to the plant location, additional electricity consumption

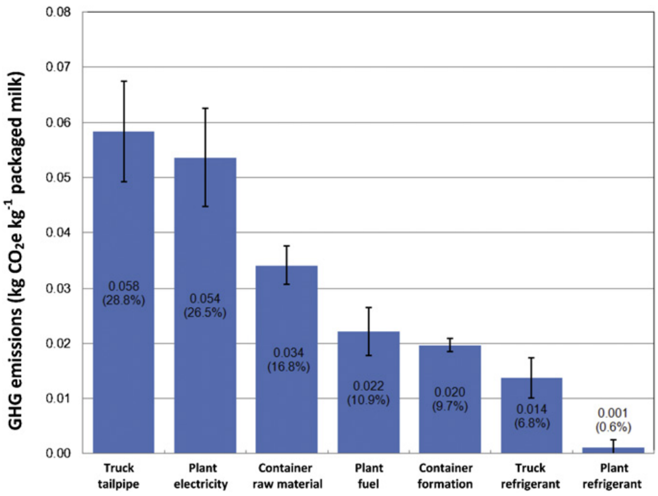

Fig. 3. Distribution of gate-to-gate GHG emissions for the fluid milk production (kg CO_2e kg^{-1} of packaged fluid milk). The numbers in parentheses account for the percentage of each on total emissions. The error bars represent the 95% confidence interval of mean.

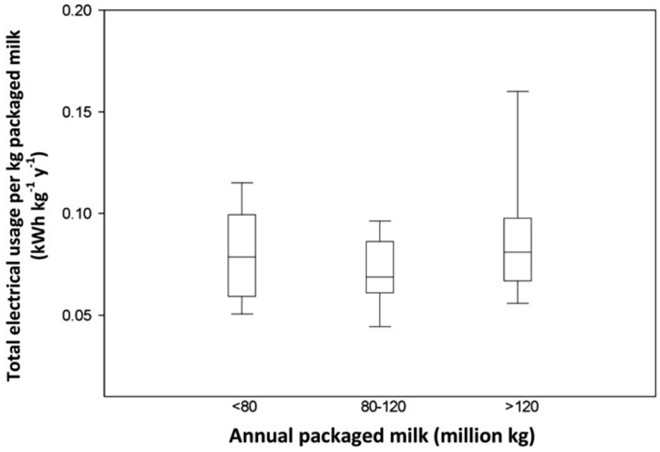

Fig. 4. Electrical energy usage per kg of packaged milk for the 50 USA fluid milk processing plants.

from ancillary equipment such as on-site waste water treatment (chemical or biological), the plant processing numerous products, thus the fluid milk is a relatively small fraction of the plant's total fluid production, plants located in the southern USA require greater refrigeration capacity and therefore higher electricity usage, and general difference in operational efficiencies. To reduce emissions, a focus on plant electricity consumption is prudent within the dairy industry since it is the second greatest GHG contributor, within this gate-to-gate study. Implementation of standard energy efficiency practices (Brush, Masanet, & Worrell, 2011) should be considered for the refrigeration system, compressed air system, motors, and lighting. Similarly, plant fuel reductions could be realized through improved steam system efficiency and operating practices.

3.1.2. Packaging emissions

Container raw material accounts for 63.0% of total packaging GHG emissions while the remaining 37.0% stems from electricity usage due to forming the container or package (e.g., blow molding). Fig. 7 shows total emissions, in metric tons of CO_2e, associated with the fluid milk packaging operations, including on- and off-site container formation and raw material manufacture. In general, the total emission data for most plants were found to be linearly proportional with annual packaged milk production. There are three primary reasons for data that fall well above the median: plants that produce large quantities of small volume containers have higher emissions due to the need for more raw material per unit milk volume, variation in efficiencies of individual blow molding equipment, and variation in electricity emission factors due to the plant location. Similarly, there are three primary reasons for data that fall well below the median value: plants that package large quantities of milk in non-plastic based containers such as paperboard, variation in efficiencies of individual blow molding equipment, and variation in electricity emission factors due to the plant location. Emission savings for packaging could come from improved bottle designs resulting in reduced material use and upgrades to modern, energy efficient formation equipment. As an example, changing the bottle cap manufacturing process from injection-molding to thermoforming may lower environmental burdens as Keoleian et al. (2004) recommended on yogurt cup manufacturing process.

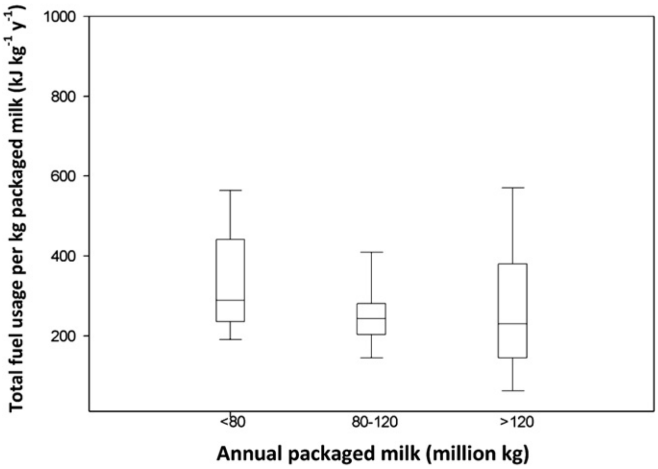

Fig. 5. Heating fuel energy usage per kg of packaged milk for the 50 USA fluid milk processing plants.

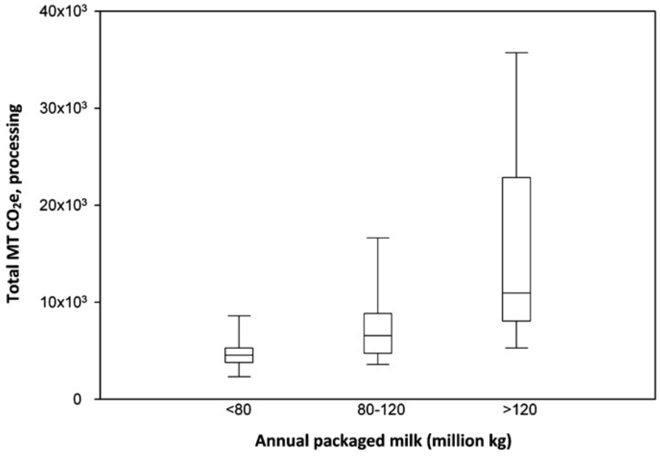

Fig. 6. Annual total GHG emissions (in metric tons, MT) by fluid milk processing operations versus annual plant production. The data include plant electricity, fuel, and refrigerant emissions. The horizontal line within the box indicates the median value, 25th and 75th (outer box edge), and 10th and 90th percentile (extremes).

3.1.3. Distribution emissions

Truck fleet tailpipe emissions from diesel fuel is the dominant portion of total distribution GHG emissions, making up 80.6%. The

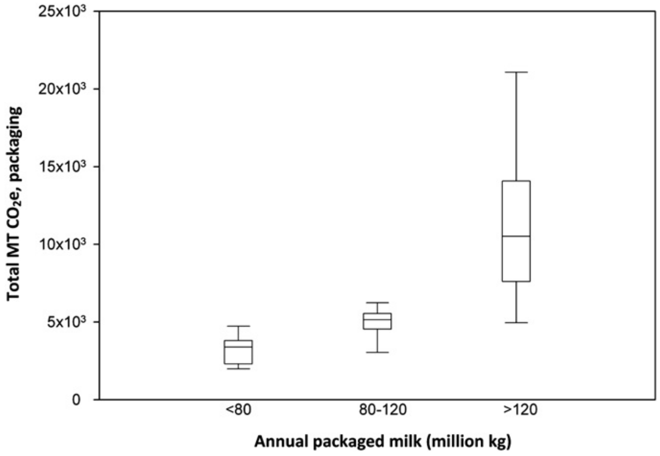

Fig. 7. Annual total GHG emissions (in metric tons, MT) by fluid milk packaging operations versus annual plant production. The data include on- and off-site container formation and material manufacture. The horizontal line within the box indicates the median value, 25th and 75th (outer box edge), and 10th and 90th percentile (extremes).

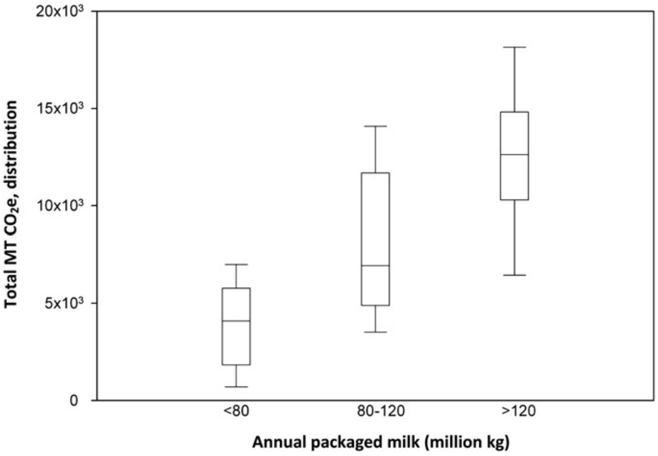

Fig. 8. Annual total GHG emissions (in metric tons, MT) by fluid milk distribution trucks versus annual plant production. The data include fuel usage to deliver packaged milk and truck fleet refrigerant use. The horizontal line within the box indicates the median value, 25th and 75th (outer box edge), and 10th and 90th percentile (extremes).

remaining 19.4% is from truck refrigerant leakage. As can be seen in Fig. 8, total distribution-related emission for individual plants correlates somewhat to annual packaged milk delivered, but with some scatter. There are several likely causes for the data variation within a given production group, including: the differences between emission factors for various refrigerants used by the refrigeration system, the location of the plant relative to the primary delivery points, and the differences caused by the customer's size of order. For example, multiple smaller milk deliveries in inner urban retail stores will have higher emissions per gallon of packaged milk as compared with whole truck deliveries of milk to large rural or suburban retail warehouse or grocery superstores. A careful study of plant specific optimization of the transport distances (i.e., truck miles) and the future selection of transport refrigeration systems using low-GWP refrigerants could lead to reduced transport emissions.

3.1.4. Comparison with related LCA data in the literature

There are very few data available related to GHG emissions from dairy processing plants. The few data available are from studies with varying boundaries, scopes, and unit processes; however, comparing these results can still be valuable. For example, Table 5 contains a comparison of results reported in four other studies. Gerber et al. (2010) is a report published through the Food and Agriculture Organization (FAO) of the United Nations. They reported GHG emissions for selected countries and regions of the world. They estimated that the average GHG emissions for European dairy processing, packaging and transport (raw and packaged) totaled 0.155 kg CO_2e kg^{-1} milk at farm gate. This value was for all dairy products and very close to one reported for fluid milk (0.155 versus 0.153 kg CO_2e kg^{-1} milk at farm gate), and the individual unit processes were similar to this study. Expected difference could be due to products, packaging types/materials, transportation vehicle performance and distances, energy emission factors (heating fuel and electricity source fuel mixes), and defined LCA boundaries. Hospido et al. (2003) provided a value for processing and packaging of fluid milk (excluding transport) representative of plants located in northwest Spain. Their value of 0.183 kg CO_2e kg^{-1} packaged milk was somewhat higher than this study's combined unit processes average value of 0.131 kg CO_2e kg^{-1} packaged milk. Differences between the two could be from packaging types/materials, plant energy use from more ultra-high temperature (UHT) thermal processing in Spain, and energy emission factors.

There are at least two examples of USA-based studies. First, Heller and Keoleian (2011) performed a robust cradle-to-grave LCA for a large vertically integrated organic dairy. Shown in Table 5 are data for the first four post-farm unit processes. In all cases, their GHG emissions were higher than the USA average determined in this study. Reasons for difference could include thermal processing (UHT versus HTST), primary packaging sizes/material, energy emission factors, allocation, and unit process boundary definitions. Tan, Nutter, and Milani (2011) looked at the GHG emissions from the energy use of a multi-product dairy processing plant. Based on process flow diagrams and a detailed mass and energy balances (Brown et al., 1996), the study found that fluid milk processing and packaging combined had emissions of 0.139 kg CO_2e kg^{-1} packaged milk, while not including any estimated upstream emissions from packaging materials. This reported value is comparable with this study's combined unit processes average value of 0.131 kg CO_2e kg^{-1} packaged milk, which does include the impact of packaging raw material. Further differences could be due to energy emission factors, boundary definitions, and allocation.

3.1.5. Overall and per kg emissions

Fig. 9 shows the total plant emissions per kg of packaged fluid milk for three divided groups of annual plant production. It can be seen that the GHG total emission intensity expressed in kg CO_2e kg^{-1} of packaged milk is not a strong function of the plant's annual volume of milk production.

Table 5
Comparison of reported green house gas (GHG) emissions for dairy and fluid milk processing, packaging, and transportation (raw milk and packaged milk distribution).

Total GHG emissions reported	Unit operations				Description and comments	Reference
	Raw milk transport	Processing	Packaging	Transport to retail or DC		
0.203 kg CO_2e kg^{-1} packaged milk		0.077	0.054	0.077	Current study described in this paper	This study
0.22 kg CO_2e kg^{-1} FPCM at farm gate	0.22[a]				Computed average for processing of all USA raw milk (all products)	Gerber et al. (2010) [b]
0.155 kg CO_2e kg^{-1} FPCM at farm gate	0.016	0.086	0.038	0.014	Estimated average values for Europe for all raw milk (all products)	
0.183 kg CO_2e kg^{-1} packaged milk	0.183[a]				Located in Spain; mix of UHT and HTST thermal processing	Hospido et al. (2003)
0.464 kg CO_2e kg^{-1} packaged milk	0.039	0.106	0.126	0.193	Organic milk; ultrapasteurization thermal processing; transport to retail includes milk storage	Heller & Keolian (2011) [b]
0.139 kg CO_2e kg^{-1} packaged milk		0.114	0.025		Computed from US DOE component mass and energy balances.	Tan et al. (2011)

[a] Unit operation not defined
[b] Values were approximated based on graphical data within the published paper.

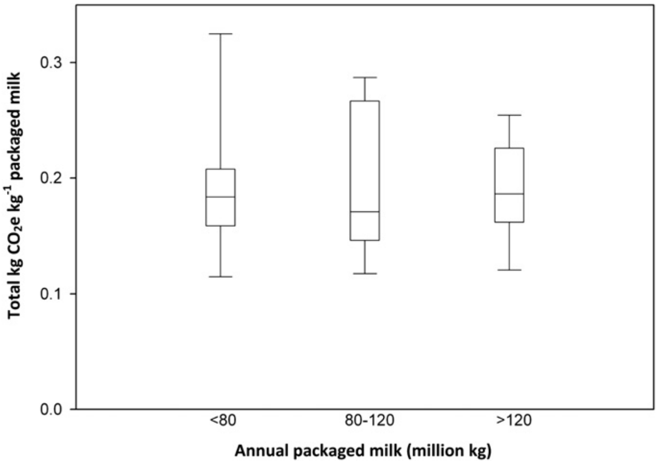

Fig. 9. GHG emissions per kg of packaged fluid milk (in kg CO_2e kg^{-1}) for the entire gate-to-gate system (sum of processing, packaging, and distribution) versus GHG annual plant production. The horizontal line within the box indicates the median value, 25th and 75th (outer box edge), and 10th and 90th percentile (extremes).

4. Conclusions

This gate-to-gate LCA was based on data collected from 50 USA fluid milk processing plants. The study evaluated the GHG emission per kg of packaged fluid milk. Average GHG emissions in various unit processes (processing, packaging, and distribution) of 50 plants were reported and discussed. The overall gate-to-gate GHG emissions were found to be 0.203 (±0.0174) kg CO_2e kg^{-1} of packaged fluid milk. Truck fleet tailpipe emission was the most intensive contributor, emitting an average of 29% of total system GHGs. Electricity usage was the next most intensive process, accounting for 27% of overall system GHGs. Overall, the importance of this study includes a breakdown of major emission contributors, their relative sizes and variation. These data are useful to populate a cradle-to-grave fluid milk LCA and spawn innovation and improvement within the dairy industry.

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