Life Cycle Assessment of Cheese Manufacturing in the United States

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ABSTRACT

A farm-gate-to-customer-gate life cycle assessment was conducted to evaluate the environmental and ecological impacts associated with US cheddar and mozzarella cheese manufacturing. Data collected from 16 cheese processing plants (ten cheddar plants and six mozzarella plants) were used to construct a life cycle inventory model, from raw milk delivery to the plant's refrigerated storage silo through delivery of packaged cheese and whey to the first customer. Our baseline allocation approach for energy and other resource use was the facility-supplied fractional estimation of co-products. Where specific information was not provided, revenue-based allocation was used for remaining inputs and emissions. The major environmental impact contributors to climate change were electricity usage (28.3% of total) followed by cheese transport and natural gas use representing 22.5% and 17.3%, respectively. Accumulated reductions in electricity consumption across the life cycle will have significant sustainability benefits. Additional metrics and normalization of the results are discussed in the document.

Keywords: Life cycle assessment, environmental impact, greenhouse gas (GHG) emission, energy use, cheese manufacturing

1. Introduction

Cheese is one of the highly recommended dairy products to consume as part of a healthy and balanced diet. However, cheese manufacturing is a complex process where a myriad of operations take place which are energy intensive. Therefore, it is necessary to estimate the environmental consequences associated with cheese manufacturing to make improvements that promote sustainability (Berlin 2002). In 2009, about 4.6 million tons of cheese products at more than 450 processing plants were produced in the United States, and there has been a trend toward increasing consumption of cheese with an average annual growth rate of 2.5% over the last decade (IDFA 2010). The production of cheese requires numerous resource inputs and outputs that contribute to environmental and ecological risks including greenhouse gas (GHG) emissions. This study provides information that will help the cheese industry to engage more sustainable practices, and reduce environmental consequences, while validating those reductions through science-based analysis. This work will also assist the cheese industry in positioning its products in the market place in terms of their sustainable attributes and be proactive with their own environmental initiatives and toward consumer concerns.

The study reported here was a part of larger effort to evaluate the cradle-to-grave life cycle assessment (LCA) of the environmental impacts associated with cheese consumption in the United States (Kim et al. 2013). This paper presents a farm-gate-to-customer-gate environmental impact analysis of cheddar and mozzarella cheese processing plants. This study focused on quantifying emissions to air, water and soil, cumulative energy demand, consumption of water and other natural resources, and assessing the impacts of inventory exchanges on climate change, resource depletion, human and ecosystem health. In particular, nine environmental impact categories associated with processing, packaging, and distribution in the production and delivery of a ton of packaged cheddar and mozzarella cheese were investigated. Cheddar and mozzarella cheese were chosen on the basis that they represent about 64% of all natural cheese produced and 80% of sales basis in the United States (IDFA 2010). The overarching goal of this work was to equip cheese industry stakeholders with timely, science-based information to further allow incorporation of environmental performance into decision-making and drive innovation.

2. Methods

2.1. Goal and scope

The main goal was to perform an analysis of potential environmental impacts associated with manufacturing of cheddar and mozzarella cheese and to provide cheese manufacturers with information to benchmark their performance against a 2009 industry average in the United States. The identification of the operations which have a major environmental impact will make possible to establish improvement actions and to quantify the impact reductions achieved. The scope of this work was a farm-gate-to-customer-gate impact assessment of a typical cheese processing plant. In particular, the specific operations included transport of raw milk to the plant, cheese and whey manufacture, and delivery of cheese and whey products to the first customer. The first customer can be a retailer for cheese and whey products, animal farm for whey as a feed, or other facility and country for further processing (Some whey is exported to China). This analysis was performed in compliance with ISO 14040 and 14044 standards for life cycle assessment (ISO 2006a; ISO 2006b).

2.2. Functional unit and system boundaries

The functional unit was defined as one ton (1,000 kg, dry-weight basis) of packaged cheddar and mozzarella cheese delivered to the plant's first customers. The system boundaries begin with the raw milk loaded into truck at the farm and end with delivery of packaged cheese and whey to the first customer via the plant's distribution truck. Landfill disposal of packaging is included in the model. In determining whether to expend project resources to collect data for the inclusion of specific inputs, a cut off criterion was established as 1% threshold for mass and energy. Exceptions to this exclusion were made in cases where significant environmental impact is associated with a small mass input. Also, if the data was readily available the elementary flow was not excluded simply because it was small. Even though the study is intended to be comprehensive in consideration of impacts resulting from cheese production, it is not a detailed engineering analysis of specific unit operations within each manufacturing facility. Thus, for example, we did not assign a specific energy requirement for the cheese making vat, cleaning-in-place (CIP), or starter culture operations; rather we used the information available at the manufacturing plant-scale, coupled with allocation of burdens to multiple plant products, to define the burden assigned to primary cheese, other cheese, dry whey, wet whey and other co-products. For this reason, it is important to state that all operations, as well as facility overhead (heating, lights, computers, etc.) are accounted in this study.

2.3. Gate-to-gate inventory data

Data collected specifically for this project were primarily derived from a survey created for cheese manufacturing plants. During 2010, processing companies that participated voluntarily were asked to complete a spreadsheet-based data entry template. Ten cheddar manufacturing facilities (0.55 million tons of cumulative production; 38% of US annual production), six mozzarella manufacturing facilities (0.35 million tons of cumulative production; 24% of US annual production) and one whey manufacturing facility responded. Collected data were based on calendar year 2009. A variety of plant sizes are represented with production ranging from 14 million kilograms per year to around 140 million kilograms per year. The average production of the 10 cheddar and 6 mozzarella plants from the survey was just less than 54 million kilograms per year of cheese, for both cheese varieties. The survey requested facility level data regarding purchases (energy, materials, chemicals, water, and truck fleet fuel), production (cheese and other products), and emissions (solid and liquid waste streams). The information was at the most refined level known by plant managers; however, in many cases only whole facility-level data were available. For example, most plants only reported a single annual electrical energy use. Plants were requested to provide an estimate for separate material and/or energy exchanges (inputs and outputs) associated solely for either cheese or whey products; this information was used to refine the allocation of material and energy exchanges between the co-products of cheese and whey on an individual flow basis. Whey processing can require more thermal energy and resource intensity per ton of finished product than cheese, depending on the degree of solids concentration. Additionally, since facilities produced other cheeses (not cheddar or mozzarella), wet whey, dry whey, other co-products (cream, butter, permeate, lactose, etc.), or a combination of these products, the delineation of the multiple co-products is important in the methodology. For the functional units chosen in this study, packaging is a re-sealable low-density polyethylene plastic bag. In addition to the primary product packaging, we collected survey information regarding secondary packaging (e.g., corrugated cardboard boxes, stretch wrap, paper bags, slip sheets and pallets). The survey also included information for transportation of raw milk to the processor, as well as distribution of final products to storage and first customer. The baseline vehicle was considered to be an insulated tanker truck for raw milk transport and a refrigerated truck for cheese or other co-products distribution. Empty return miles were also accounted. SimaPro© 7.3 (PRé Consultants, The Netherlands 2012) was used as the primary modeling software; the ecoinvent database, modified to account for US electricity (use of the average US grid excludes the variation in the results by region, EarthShift 2012), provided information on the 'upstream' burdens associated with materials like primary fuels and plant chemicals.

2.4. Life cycle impact assessment

We adopted the ReCiPe (Goedkoop et al. 2009) and the USEtox (Rosenbaum et al. 2008) methods with an additional inventory category, cumulative energy demand (Hischier et al. 2010). The two inventory categories, non-renewable fossil fuel (cumulative energy demand) and water depletion (ReCiPe inventory indicator), and the seven impact categories: climate change (IPCC GWP 100a), freshwater and marine eutrophication (ReCiPe midpoint), photochemical oxidant formation (ReCiPe midpoint), ecosystems (ReCiPe endpoint), human health (USEtox), and ecotoxicity (USEtox) are presented quantitatively. ISO 14044 standards do not permit combining multiple metrics into a single score, therefore the results of this study were reported as individual metrics for each of the impact categories.

2.5. Allocation

There are five potential co-products in this work. Because a variety of whey handling technologies are commonly used in the industry, allocation decisions are critically important. Some plants have virtually no processing of the whey after it is removed from the cheese vat, other plants have major processing of the whey making various protein concentrations or dried powders. Data is most commonly available only at the whole plant level. Therefore, to properly account for the energy and impacts that should be allocated to multiple products, a careful accounting of the differences in whey processing is included.

Some of the unit processes are unique to individual products and others are common to all other co-products. For all processes that can be clearly defined as being associated with a single product was assigned to that product. In the survey of manufacturing facilities, we asked for engineering estimates of the allocation of common inputs and emissions to internal facility operations and co-products. In addition, we collected the distribution of gross revenue generated by all the co-products from the facility. For inputs and emissions, these estimated allocation fractions were used as our principal source of information. For energy and other resource use in the plant, we used the plant-supplied engineering allocation. If the plant did not provide engineering estimated allocation fraction, we used an allocation based on the reported fraction of plant revenue assigned to that product. The burdens from milk production and transport were allocated based on the distribution of milk solids using the Van Slyke equation (van Slyke and Price 1979) which estimates the theoretical yield of cheese and whey products based on the incoming raw milk fat and protein content.

3. Results

3.1. Environmental impact assessment results

The inventory information collected from the surveys was converted into lifecycle inventory datasets, coupled with ecoinvent datasets and analyzed using SimaPro 7.3 software. Because the units of measure for each impact category are dissimilar, we report results as a contribution analysis by production inputs. Processing-related operation impacts were grouped into six categories: electricity, natural gas, fuel oil, chemicals, water and wastewater treatment. Packaging-related impacts were grouped into five categories: corrugated board, plastics, pallet, plywood and disposal. Distribution-related impacts were grouped into three categories: cheese transport, raw milk transport and other transport. Other transport here includes the transport of purchased chemicals, packaging materials, cream, and ingredients such as starter media, salt and rennet, etc. On cheddar cheese analysis, electricity usage contributes the largest impacts to climate change with 46.6% on processing stage followed by natural gas and chemical usage with 28.4% and 10.8 %, respectively. Packaging stage does not have significant environmental impacts representing only 7.7% contribution overall to climate change. On distribution stage, cheese transport stands for the largest contributor across all nine impact categories making up about 71.5% contribution followed by raw milk transport, 19.4% contribution to climate change. On overall interpretation from farm-gate-to-customer-gate, electricity usage contributes the largest impacts to climate change with 28.3% followed by cheese transport and natural gas use with 22.5% and 17.3 %, respectively. Similar results as climate change are observed on cumulative energy demand, thus these are not explained here. The freshwater depletion is dominated by processing stage, due to process water usage mostly for cleaning-in-place (CIP), representing 90.8%. The eutrophication impacts are affected by on-site wastewater treatment (WWT). The unit process for whey digestion was adapted from the ecoinvent dataset. This unit process is based on modern technology from Switzerland, and should be generally applicable in the US; however, the incineration of sludge is included in the original dataset, and this is not a common practice in the US. Thus, exchanges in the dataset which were identified as deriving from sludge incineration were removed. In addition, the assumed phosphorus loading to the treatment facility, for Swiss conditions, was 250 mg/L. Based on the survey and literature (Danalewich et al. 1998) reports, we reduced the WWT influent total phosphorus to 70 mg/L. The survey data were highly variable with some reporting post-treatment concentrations. Furthermore, not all plants reported P loadings so the average estimated load was used for all facilities. Freshwater eutrophication is driven by phosphorus loading, and for the impact assessment framework chosen for this study, there was no differentiation between phosphorus emitted directly into receiving waters and phosphorus applied to land with sludge. For marine eutrophication, which is driven by nitrogen emissions, we did not have any information in the survey, and therefore adopted the ecoinvent WWT dataset influent loading and emissions profile. Nitrogen compounds which are emitted are generally in a soluble form, and due to the prevalence of phosphorus limitations in freshwater, an assumption that all N emitted ultimately reaches marine waters is made in the impact methodologies. Because the WWT process is the dominant source of eutrophication, and the uncertainties associated with the inventory and impact methodologies, further evaluation of the damages actually resulting from WWT is needed. This analysis shows that there is a potential impact associated with these emissions, but does not demonstrate the fact of this damage to the environment. The photochemical oxidant formation impact is dominated by distribution stage representing 65.5% followed by processing stage which makes up 28.8% of overall. The primary driver to this impact is observed to be nitrogen oxides (NOx) emissions which are stem from truck tailpipe. Volatile organic compounds emissions from combustion associated with transport and manufacturing are also noticeable drivers. The ecosystems damage is also affected most by processing stage with 55.8% of overall. The primary driver to this impact is carbon dioxide emissions associated with electricity generation and heating fuel combustion followed by forestry for corrugated board packaging. The human toxicity and ecotoxicity impacts show similar result pattern dominated by processing stage which represents 77.1% and 66.0% of overall, respectively. The largest contributor to these impacts is heavy metal emissions to both air and water primarily driven from coal mining tailings and coal ash disposal in the electricity supply chain. However, these results should be interpreted with care because USEtox characterization factors for metals are highly uncertain according to Rosenbaum et al. (2008). A discussion of major contributors to each impact category is provided in Table 1 which is applicable for both cheddar and mozzarella cheese.

Table 1. Gate-to-gate drivers across environmental impact categories for both cheddar and mozzarella cheese.

Damage category	Major gate-to-gate impact drivers
Climate change	CO_2-equivalent emissions from fossil fuels combustion related to electricity generation, on-site heating fuels usage and diesel usage
Cumulative energy demand	Energy demand by electricity generation, natural gas usage and diesel fuel usage
Freshwater depletion	Process water usage
Marine eutrophication	Nitrogen compounds released into water from wastewater treatment; likely associated with nitric acid used in CIP operations
Photochemical oxidant formation	NOx and VOCs emissions from combustion associated with transport and manufacturing
Freshwater eutrophication	Phosphorus emissions associated with wastewater treatment with smaller impacts associated with manufacturing from coal mining for electricity generation. Phosphorus is likely emitted during CIP operations where milk protein residues are removed from piping and equipment
Ecosystems	Majority from CO_2 emissions associated with electricity generation, heating fuel and transport combustion; secondary from forestry for corrugated board packaging.
Human toxicity	Arsenic emission to water and heavy metals emissions to both air and water primarily from coal mining tailings and coal ash disposal in the electricity supply chain
Ecotoxicity	Chromium emission to water and heavy metals emissions to both air and water primarily from coal mining tailings and coal ash disposal in the electricity supply chain

3.2. Cleaning-in-place (CIP)

The cheese manufacturing industry has been active for many years in addressing the important issues associated with CIP technologies and chemical usage. As described in the previous section, CIP is a contributor to several impact categories. However, one of the limitations of the data available for this study was that only whole-plant information and therefore detailed analysis of the CIP was not possible. Specifically, not all chemical purchases, or energy consumption at the whole plant level could be attributed to CIP, thus the emphasis of manufacturers on managing CIP impacts remains important. Sustainability will be achieved through continual incremental improvement, and these improvements across many plants will cumulatively have a significant and measurable impact at the sector level. The granularity of data in this study highlights the need for further investigation at the plant level.

3.3. Normalization

We conducted a normalization test using the Impact 2002+ US midpoint assessment framework which was published by Lautier et al. (2010). The result for cheddar indicates that aquatic ecotoxicity is the largest relative impact in the US context. The primary driver of the aquatic ecotoxicity is aluminum emissions associated with digestion of wastewater from whey processing and treatment for an effluent containing spilled milk or milk residue removed by CIP. Aluminum in the WWT procedure is used as a coagulant to remove phosphorus via chemical precipitation. The ecotoxicity impact associated with cheese manufacturing represents approximately 0.47 percent of the annual US ecotoxicity impact. It reaches about 0.89% combining cheddar and mozzarella. Because nearly identical result was observed with mozzarella, normalization result on mozzarella is not included here. Terrestrial ecotoxicity and aquatic eutrophication are the next important categories to focus improvement activities. From a manufacturing perspective, these can be mitigated through energy conservation and water conservation/treatment activities.

3.4. Uncertainty analysis

The uncertainty in the results was evaluated using Monte Carlo simulation, available in SimaPro 7.3 software. The ecoinvent pedigree matrix approach was applied to each exchange generated from primary data and then the resultant inventory uncertainty is calculated. These results which are based on a dry solid basis can be used to approximate the impacts on as-sold moisture basis (63.2% solids for cheddar, 51.4% solids for mozzarella). GHG emissions are of notable interest, and on dry-weight basis, the GHG emissions of cheddar and mozzarella are approximately 1.29 and 1.81 tons CO_2e per ton of cheese solids delivered, respectively. The 95% confidence band ranges 0.92 to 1.77 tons CO_2e per ton of cheddar cheese solids delivered, and 1.24 to 2.62 tons of CO_2e per ton of mozzarella cheese solids delivered. For an average moisture content of 36.8% for cheddar as sold at retail, the GHG emission is 0.82 ton CO_2e per ton cheddar delivered with a confidence band of 0.58 to 1.12 tons CO_2e per ton cheddar delivered. Based on an average moisture content of 48.6% for mozzarella as sold at retail, 0.93 ton of CO_2e per ton mozzarella is emitted, with a 95% confidence band of 0.64 to 1.35 tons CO_2e per ton mozzarella delivered. On a dry-weight basis, the freshwater depletion – defined as water removed during the production, but not returned to the same watershed – is 15.7 m^3 per ton of cheddar delivered with 95% confidence band of 12.9 to 19.4 m^3 of water consumed per ton of cheddar delivered. This is equivalent to approximately 9.9 L of water per kilogram of cheddar cheese delivered in the United States. For mozzarella cheese, 13.6 L of water are consumed per kilogram of mozzarella delivered. It should be noted that, even though the same allocation scheme was used for both cheeses, the variability of the co-products for typical cheddar plants and mozzarella plants make direct comparisons of environmental impact results between the two cheese products very difficult and inadvisable.

3.5. Estimated industry scale contribution to US GHG inventory

An estimate of the entire cheese sector impact from farm-gate-to-customer-gate was made through inclusion of the whey and other co-products produced. In reported surveys, mozzarella manufacturing facilities did not produce significant quantities of other cheeses. Cheddar facilities did report some production of Monterey Jack, Swiss, and other natural cheeses. Taking the assumption that all cheeses other than mozzarella had a similar production impact as cheddar manufacturing facilities coupled with whole-plant data, the cheese sector impact was estimated by scaling the study results to national scale. In 2009, about 4.6 million tons of cheese products were produced in the United States (IDFA 2010). The total GHG emissions as sold at retail, including whey and other co-products, are approximately 3.5 million tons CO_2e; cumulative energy demand of 4.7e10 MJ (roughly equivalent to 8.2 million barrels of oil); water consumption of 32 million cubic meters of water.

4. Discussion

From a manufacturing perspective, the study suggests some opportunities to reduce individual plant impacts. First, a focus on plant electricity consumption is explicit since it is the single greatest impact driver. Implementation of energy efficiency best practices 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. Minimizing the amount of water and energy used for CIP can be achieved through using reuse or recovery distribution systems (Baskaran et al. 2003). Finally, careful study of plant specific optimization of the transport distances and the future selection of transport refrigeration systems using low-GWP refrigerants could lead to reduced emissions for the cheese industry.

5. Conclusion

Average impacts in various unit processes (processing, packaging, and distribution) were reported and discussed. For an average moisture content of 36.8% for cheddar as sold at retail, the GHG emission is 0.82 ton CO_2e per ton cheddar delivered with a 95% confidence band of 0.58 to 1.12 tons CO_2e per ton cheddar delivered. Based on an average moisture content of 48.6% for mozzarella as sold at retail, 0.93 ton of CO_2e per ton mozzarella is emitted, with a 95% confidence band of 0.64 to 1.35 tons CO_2e per ton mozzarella delivered.

For the post-farm supply chain, climate change and cumulative energy demand impacts are closely linked with fossil fuel consumption primarily associated with coal mining and combustion. The impacts associated with the electricity supply chain and combustion of other fossil fuels was found to be the most intensive contributor within nearly all impact categories including climate change, cumulative energy demand, ecosystems, human toxicity, and ecotoxicity. Thus conservation efforts to reduce electricity and fuel use will have broad beneficial consequences for environmental sustainability. Truck fleet tailpipe emission is also observed to be a significant impact driver. Thus, seeking the most appropriate transport modes and methods to mitigate the impacts on the environment will deliver financial benefits as well as boost a company's reputation in the minds of consumers.

The regionalized normalization analysis based on an average US citizen's annual cheese production showed that aquatic ecotoxicity stands for the largest relative impact due to aluminum emissions associated with digestion of wastewater from whey processing. Terrestrial ecotoxicity and aquatic eutrophication indicate the next significant impact categories. Therefore, incorporating best practices around heavy metals, phosphorous and nitrogen emissions management can yield good improvements.

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