Fermentation and distillation of cheese whey: Carbon dioxide-equivalent emissions and water use in the production of whey spirits and white whiskey

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ABSTRACT

Whey disposal can be both an environmental and economic challenge for artisanal creameries. Lactose in whey can be fermented to produce ethanol and subsequently distilled. The objective of this study was to use a process-based life cycle analysis to compare carbon dioxide-equivalent (CO₂e) emissions and water usage associated with the artisanal or craft production of clear, unaged spirits using whey or malted barley as fermentation substrate. Differences in production were assessed based on key process differences: energy used, water used, distillation by-product disposal, and mass of CO₂ produced during fermentation. For this study, whey was assumed removed from the artisanal creamery waste stream. Quantifiable differences were evaluated per 750-mL (45% alcohol by volume) functional unit and expressed as mass-equivalent CO₂ emissions (kg of CO₂e) and mass of water (kg) used. The CO₂e emissions and water usage were quantified using published data, thermodynamic calculations, and mass-balance calculations for a hypothetical distillation system. The process-based life cycle analysis estimated that distillation of fermented whey reduced overall CO₂e emissions by 8.4 kg per functional unit and required 0.44 kg less water added into the production process compared with production of a similar clear, unaged spirit using malted barley as substrate. Our preliminary analysis suggests that conversion to distilled whey spirit is a more environmentally responsible approach compared with landfill disposal of whey.

Key words: carbon, life cycle analysis, artisanal creamery waste, distilled whey spirit

INTRODUCTION

The hallmark of a sustainable business is a balanced approach to economic, environmental, and social responsibility—a sustainable business aims to have a positive role in the community while maintaining profitability. In the dairy industry, particularly among small and medium-sized artisanal cheese makers, whey remains an important waste effluent that can have a profound impact both economically and environmentally. Whey consists of 93 to 94% water and contains lactose, protein, minerals, lactic acid, and fats (Prazeres et al., 2012). The concentration of lactose (4.5–5.0%) in whey gives it a biochemical oxygen demand (BOD) of 30 to 50 g/L and chemical oxygen demand (COD) of 60 to 80 g/L (Siso, 1996; Guimarães et al., 2010; Chatzipaschali and Stamatis, 2012). Much of the whey produced today is converted to value-added powders, which requires technology operating at a scale that is not commercially viable for artisanal creameries.

Instead, small to medium-sized artisanal creameries dispose of whey using traditional methods, such as land disposal, animal feed, or at a municipal or private water treatment facility. Several problems are associated with such disposal of whey, including cost due to shipment of whey, fees charged by waste management facilities, and limits imposed on production volumes due to local environmental restrictions. Thus, there is a need to develop low-cost technologies to convert small volumes of whey into value-added products.

Research into using cheese whey as a substrate for ethanol production has been ongoing for the past 75 yr (Whittier, 1944; Rogosa et al., 1947; Guimarães et al., 2010) and has focused primarily on fermentation optimization. During fermentation, sugar is converted into ethanol and carbon dioxide at a near-equal (wt/wt) ratio (Lewis and Young, 2002). Under ideal conditions, raw fermented whey yields 2 to 3% (wt/vol) ethanol (Koushki et al., 2012). Many strains of *Kluyveromyces marxianus* have the ability to break down lactose into fermentable sugar monomers without the need for further processing (Dragone et al., 2011; Diniz et al.,

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2014; Hadiyanto et al., 2014). In spite of interest in whey as a substrate for ethanol production, relatively little research has focused on the use of fermented whey to produce a distilled whey spirit (**DWS**) for human consumption. Research related to consumable DWS has included the gas chromatography analysis of volatile compounds found in DWS and subsequent comparison to traditional spirits (Dragone et al., 2009). The craft spirit market has been expanding steadily for the last 10 yr (Lozier, 2017) and the development of novel products could allow distilleries to develop an economic edge. Currently, several craft distilleries are producing commercial examples of “milk vodka,” such as Black Cow vodka (Black Cow, 2017) and Vermont White vodka (Vermont White, 2016).

This study compared the environmental impact of DWS production to that of an unaged, clear spirit produced from malted barley, commonly referred to as white whiskey (**WW**). The justification for comparing DWS with WW production is the assumption that DWS would replace other clear spirits on the market and should therefore not have a negative environmental impact compared with existing clear spirits. Ideally, removal of unprocessed whey from a creamery waste stream should effectively reduce the overall environmental impact of the latter.

White whiskey is frequently produced by craft distillers, who would be logical end-users of whey generated by small, artisanal creameries. It should also be noted that the production processes for WW and DWS are similar; a distillery producing WW could easily shift production to DWS without the need for additional investments in infrastructure. Each process produces an unaged, clear spirit that could be marketed as a craft spirit and sold at a premium price.

MATERIALS AND METHODS

A process-based life cycle analysis (**LCA**), following the ISO 14040 and 14044 frameworks (ISO, 2006), was used to compare the differences in processes and environmental impacts (Scientific Applications International Corporation, 2006). The process-based LCA consists of 4 steps, which are used to identify goal and scope of LCA, define processing input and outputs, quantify key environmental impacts, and draw conclusions from the information obtained (Figure 1). Environmental metrics were determined in terms of mass of CO₂-equivalent greenhouse gases (CO₂e, kg) per functional unit and mass of water per functional unit. The functional unit was defined as 750 mL of 45% ethanol, a common commercial unit within the distilled spirits industry (Alcohol and Tobacco Tax and

Trade Bureau, 2012) and will be referred to hereafter as a bottle of spirit. Data were collected at the stages in which inputs and outputs differ in the production process. Each step of the process was considered for all major energy inputs, waste outputs, and CO₂ produced during fermentation.

Goal and Scope

The goal of this study was to compare CO₂e emissions and water use for the production of 45% alcohol by volume (**ABV**) spirits. This study evaluated energy and water input required to produce a bottle of spirit using materials already present on site. Sustainable energy and water use are integral to ensure responsible food production practices to meet the demands of a growing global population (Flammini et al., 2014). The choice to evaluate energy and water inputs enabled us to quantify environmental impacts, and these inputs are common industry measurements used to determine environmental impacts of food and beverage production (Kim et al., 2013; Tsiropoulos et al., 2014; Eriksson et al., 2016). The scope of this study was confined to distillery operations. Thus, only differences in production methods were considered. Other materials and processes used for the production of craft spirits (e.g., agriculture production processes, shipping, packaging, and malting) are common across multiple industries and would not be affected by artisanal spirit production, so they were excluded from the scope of analysis. The process flows for WW and DWS production are outlined in Figure 2. The scope of this study began with the raw fermentation substrate received at the facility and ended before packaging, with the final product be-

Figure 1. Steps in a life cycle analysis.

ing diluted to bottling strength, because each product's environmental impacts would be identical beyond this point. The first and greatest difference between the

individual products is the removal of all steps before and including "mash" in the DWS process. This is a key point in the overall scope of the study: mashing is a

A.

B.

Figure 2. Flow diagrams for (A) white whiskey process, and (B) distilled whey spirit process.

Table 1. Assumptions used to compare white whiskey (WW) and distilled whey spirit (DWS) production

Parameter	Assumption and explanation
Distillery raw materials	All fermentation substrates are available at the distillery and transportation of substrates is not taken into account.
Whey	Whey is a creamery waste product with an assumed density of 1.0025 kg/L.
Whey disposal	Whey that is land spread is considered landfilled and was quantified using the EPA WARM tool (EPA, 2016). Six tonnes of CO ₂ equivalents (CO ₂ e) was produced for every 10,000 L of whey produced. Landfill location was assumed to be in Oregon; national average and typical operation was used concerning landfill gas control systems and landfill recovered methane for energy; and landfill was considered to operate under wet conditions. Distillery and landfilling sites were considered equidistant from the creamery, so transportation distances were not taken into account.
Removal of whey from a waste stream	Whey was destined to be land spread by the creamery and was calculated to have negative CO ₂ e produced during the spirit production process; this is due to the EPA credit given by the program WARM.
Grain used in WW production	Considered to be 2-row malted barley with specification obtained from Briess Malt and Ingredients Co. (Chilton, WI).
WW production	Standard brewing calculations (Lewis and Young, 2002; Holle, 2003) were used to determine the mashing specifications, including mass of malt (2,159 kg), required strike water temperature and mass (73.3°C and 6,477 kg), and required sparging water temperature and mass (76.5°C and 5,574 kg). The water's starting temperature was assumed to be 20°C.
Spent grain	The CO ₂ e produced from spent grain was quantified using the EPA WARM tool with the same parameters that were used to quantify whey disposal. The mass of the malt was estimated to produce one metric ton of CO ₂ e greenhouse gases.
Wash	The WW was assumed to be 6% alcohol by volume (ABV) and DWS was 2.5% ABV based on industry practice.
Fermentation of substrate	Yeast nutrient additions were considered identical for each substrate. Fermentation was assumed 100% efficient for both WW and DWS production to determine CO ₂ production during fermentation.
Fermentation effluent	The mass of the spent yeast from each wash was considered to be identical.
Distillation system	The distillation system used was a 2-pot distillation system.
Ethanol concentration	The WW ethanol concentration at completion of distillation was estimated to be 18.2% ABV after first distillation, 21.7% ABV after feint and foreshot addition, and 68% ABV after final distillation. The DWS ethanol concentration was based upon alcohol and water vapor equilibrium curve, estimated to be 7.5% ABV after first distillation, 9.2% ABV after feints and foreshot addition, and 48.0% ABV after final distillation.
Distillation energy calculations	The WW and DWS distillations were assumed to have identical radiative and convective heat loss because they use the still configurations.
CO ₂ e production from energy use	CO ₂ e was calculated based on a natural gas combustion factor from the US Energy Information Administration (50.3 kg of CO ₂ e per GJ; EIA, 2016).
Cooling water	Condenser water was allowed to cool to ambient temperature before discharge and no contamination occurred during cooling.

well-known and documented process (Lewis and Young, 2002; Holle, 2003) and requires the inputs of large quantities of water and energy. Traditional whiskey production relies on producing a mash, which extracts and converts grain starch into fermentable sugar.

Life Cycle Inventory

The life cycle inventory portion of the LCA included quantification of the materials, energy, and water requirements for each of the processes considered within the system boundary. Resource quantification was achieved through calculations related to hypothetical energy and water requirements, mass balance calculations throughout the processes, and logic-based assumptions as described below. Key assumptions are addressed in Table 1.

Fermentation Microorganisms

The 2 processes utilized different yeasts. *Saccharomyces cerevisiae*, the standard organism used in whiskey wash fermentation, ferments the extract produced by the mashing process (Lewis and Young, 2002) but cannot ferment lactose. Instead, *K. marxianus*, a lactose-fermenting yeast, is used to ferment whey. The environmental implications for using *K. marxianus* over *S. cerevisiae* are not well understood; however, both organisms offer distinct advantages and disadvantages. In terms of an environmental impact evaluation approach, *K. marxianus* is more thermotolerant than *S. cerevisiae* (Guimarães et al., 2010), which could play a role in energy savings, particularly in the summer months when fermentors must be thermo-regulated to maintain optimal fermentation temperatures around 30°C for WW

and 37°C for DWS. These potential energy savings were not accounted for in the LCA. The yeast input and outputs for the fermentation process for each process flow were assumed the same. Although the yeasts are different, each organism is generally recognized as safe (Raimondi et al., 2013; FDA, 2016), which allows both types to be disposed of as animal feed. Therefore, yeast disposal was not considered in the LCA.

Effluent

Effluent generation was tracked throughout the whole process. The amount of effluent for distilling included the pot ale removed from the wash still and the spent lees removed from the spirit still (Figure 3). The volume of pot ale waste leaving the wash still was calculated to be equal between WW and DWS production and was not included in the LCA. The assumption was made that the distillery was in operation twice a week, giving condenser water time to cool to ambient temperature before entering the municipal water system.

Energy Input

Energy uses in the distillation process were calculated based on a model distillation system flowchart based on standard industry practices (Figure 3). The actual distillation process was assumed identical for each product. However, inputs into the system were different because of differences in percent ABV of the fermented substrate (2.5% ABV for DWS and 6% ABV for WW), which affects energy input. The %ABV of the WW after each distillation was determined using common industry conventions and a mass-balance flowchart (Piggot, 2009; Hughes and Buxton, 2014; Nicol, 2014). The %ABV of DWS after each distillation was determined using a vapor-liquid equilibrium graph from Purdue University (Kvaalen et al., 1984) and a mass-balance flowchart (Figure 3).

Energy requirements for the distilling process were tracked based on ethanol and water ratios by mass flows within the system. Established standard reference tables were used throughout the mass-balance process to determine the density of ethanol-water solutions and to convert %ABV to percentage alcohol by weight (International Organisation of Legal Metrology, 1973).

The required energy to bring each component (ethanol and water) up to 95°C in the wash still and 90°C in the spirit still from 20°C were calculated separately for each process flow. The energy required to evaporate each component was also taken into account. These calculations were made using standard heat-transfer and

vaporization equations (Singh and Heldman, 2014), as shown below.

Equation [1] gives the energy for heat transfer:

$$Q = M \times C_p \times \Delta T, \quad [1]$$

where Q = energy (kJ), M = mass (kg), C_p = specific heat ($\text{kJ} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$), and ΔT = change in temperature ($^\circ\text{C}$).

Equation [2] gives the energy of vaporization:

$$Q = M \times L, \quad [2]$$

where Q and M are as defined above and L = latent heat of vaporization ($\text{kJ} \cdot \text{kg}^{-1}$)

Heat loss throughout the distillation process was assumed identical for each production process and therefore not included. The calculation method and process flowcharts are adapted from known whiskey still configurations and use standard thermodynamic relationships as described above (Hughes and Buxton, 2014; Nicol, 2014; Singh and Heldman, 2014).

Water Input

Water going into the distillation process was split into 3 categories: (1) water in—to condense the distillate; (2) waste water—water leaving the system from the spirit still; and (3) water for dilution—water used to bring the final distillate to the proper functional unit ethanol concentration.

Water usage in the 2 processes, except for dilution volume, was assumed identical and not a contributing factor to overall environmental impact of the distillation process. We assumed that water was recycled and not contaminated in any meaningful way. Wastewater was assumed to consist of water and spent lees from the spirit and was assumed to be disposed through the municipal water system. Water for dilution of the spirit to 45% ABV varied due to differences in initial %ABV of the 2 distillates: WW required a dilution from 68% ABV and DWS required a dilution from 48% ABV to a commercial strength of 45% ABV.

Mash Step

To assess the environmental impact of the removal of the mash step (Figure 4), energy, total mass of grain required, and water usage were quantified. The amount of grain and water required were calculated by developing a recipe that would produce a 6% ABV wash using brewing calculations (Lewis and Young, 2002; Holle,

A. **B.**

Figure 3. Pot distillation process for (A) distilled whey spirit (DWS), and (B) white whiskey (WW). ABV = alcohol by volume.

2003), such as that in Equation [3] for calculating the grain mass to be added:

$$\frac{\text{wort volume} \times \rho \times SG \times {}^{\circ}P}{\% \text{ extract} \times (1 - \% \text{ moisture}) \times \omega} = Mass_{\text{grain}}, \quad [3]$$

where ρ = density of water (kg/L), SG = desired beer specific gravity with reference of density of water, ${}^{\circ}P$ = desired Plato (grams of solute/grams of solution), % extract was on a dry basis, coarse grind (value from malt specification sheet), % moisture = percentage of

Figure 4. Mashing process for white whiskey production.

moisture from malt specification sheet, and ω = brewhouse efficiency (varies from site to site).

The malt specifications were obtained from a specialty malting supply company (Briess Malt and Ingredients Co., 2016) and are noted in Table 2. The total volume of water required by the mashing process was determined by taking into account water retained by the grain (0.96 L/kg of malt), assuming there were no evaporative losses and considering the volume of wort required for the recipe. The mashing process included 2 steps, the addition of strike water and addition of sparge water, as noted in Figure 4. The temperature and volume of the strike water were determined using common brewing conventions, including water being added at a 3:1 (wt/wt) water:grain ratio, the specific heat of grain being 40% of that for water, and the desired mash temperature being 67°C (Lewis and Young, 2002; Holle, 2003). This phase converts the starches in the mash to fermentable sugars. The required temperature for the strike water was determined to be 73.3°C based upon

the recipe detailed in Table 2. The second phase of the mashing process, a drainage/continuous sparge, is used to rinse the grains of any fermentable sugars that remain after the strike water is drained. According to common brewing conventions, sparge water is heated to 76.5°C and the remainder of the total determined volume of water is used during drainage/continuous sparge step (Lewis and Young, 2002; Holle, 2003). After the required water temperatures were determined for each mashing step, the amount of energy required to raise the water temperature to the desired level from 20°C was calculated using the thermodynamic calculations detailed in equation [1] (Singh and Heldman, 2014).

Substrate Pretreatment

To ensure healthy, successful fermentations, each substrate would be treated with yeast nutrient and diammonium phosphate; these additions were considered identical. Industrial cheese producers have the capability to process whey to recover fat and protein via centrifugation and membrane filtration (Tetra Pak, 2015a). Whey permeate processed in this manner would still provide a viable fermentation substrate. The processing of whey in this manner falls outside the pre-determined system boundary. This study assumed that whey had not been processed in this manner because artisanal creameries generally lack the required infrastructure and equipment need for such processing. If whey permeate were used as a fermentation substrate, it could reduce water used during the cleaning process.

Table 2. Mash recipe and grain specifications

Parameter	Specification
Specific gravity (SG)	1.057
Extract (° Plato)	14 g/100 g of solution
Water density (ρ)	1 kg/L
% Extract (dry basis)	0.795
% Moisture	0.042
Brewhouse efficiency (ω)	0.90

Emissions of CO₂ from Fermentation

The CO₂ generated during fermentation was taken into account as it represented a direct source of CO₂ produced in the process. Theoretically, for every 1 kg of fermentable substrate, 0.538 kg of ethanol and 0.462 kg of CO₂ are generated (Koushki et al., 2012). Using this assumption, an estimate of the mass of CO₂ emitted during fermentation could be determined based upon the mass of the ethanol produced by the yeast. The fermentations were assumed ideal and did not account for the conversion of substrate for cell mass growth, with DWS wash starting at 2.5% ABV and WW wash starting at 6% ABV. Each fermentation substrate has a similar protein content (Jancar et al., 1983; Tetra Pak, 2015a) so any treatments to prevent foaming during the distillation process or post-distillation cleaning process were considered identical. The mass of ethanol was calculated assuming an ethanol density of 789 kg/m³ (International Organisation of Legal Metrology, 1973). Once the mass of ethanol was calculated, the mass of CO₂ produced during fermentation could be found using the example calculation shown below:

$$10,000 \text{ L} \times 6\% \text{ ABV}$$

$$= 600 \text{ L of ethanol} \times \frac{1 \text{ m}^3}{1,000 \text{ L}} \times 789 \text{ kg/m}^3$$

$$= 473.4 \text{ kg of ethanol};$$

$$\text{CO}_2 = 473.4 \text{ kg of ethanol} \times \frac{0.462 \text{ kg of CO}_2}{0.538 \text{ kg of ethanol}}$$

$$= 406.5 \text{ kg of CO}_2.$$

In addition to direct CO₂ emissions, indirect CO₂e emissions were estimated by examining the energy use of the 2 production systems. The difference in required heating energy from natural gas combustion for the 2 systems was calculated. Next, CO₂e emissions were determined using an emissions factor of 50.3 kg of CO₂e per GJ for natural gas (EIA, 2016). The Waste Reduction Model software tool (WARM v.14; [https://www.epa.gov/warm/versions-waste-reduction-model-warm-#WARM Tool V14](https://www.epa.gov/warm/versions-waste-reduction-model-warm-#WARM%20Tool%20V14)) developed by the US Environmental Protection Agency (EPA; EPA, 2016) was used to estimate both the reduction of CO₂e emissions from removing whey from a waste stream and the impact of grain disposal in terms of CO₂e emissions.

Life Cycle Impact Assessment

As mentioned above, life cycle impact assessment was completed to compare the 2 systems using 2 metrics: greenhouse gas production (kg of CO₂e) and water us-

age (kg of water). The WARM software tool (EPA, 2016) was used to quantify the impact of spent grain waste from the mashing process and removal of whey from the dairy waste stream on the environment in terms of CO₂e production. The WARM tool allowed us to categorize the waste materials and provided a calculator to determine the mass of CO₂e emitted per tonne of material based on the categorization of waste. Spent grain was categorized as grain waste and whey was categorized as dairy waste. The mass of a 10,000-L batch of whey was calculated using industry data on milk density (Tetra Pak, 2015b).

The whey was given a credit for CO₂e emissions (negative value for CO₂e emissions) because it was removed from a waste system. In the WARM tool, we considered whey to be landfilled due to the practice of field spreading used by many artisan cheese companies. Because the distillery and landfill were assumed equidistant from the creamery, the travel distance from the creamery to the landfill was set at zero in the calculator to avoid factoring in vehicular emissions (i.e., no net difference in emissions). Grain waste was considered landfilled and converted to mass of CO₂e emissions using the WARM tool. The calculated energy values were converted to mass of CO₂e emissions based on the energy produced through burning of natural gas.

Sensitivity Analysis

The CO₂e emissions were changed by $\pm 25\%$ for each production step listed in Table 4, and impact to total CO₂e emissions produced by each production process was tracked.

RESULTS AND DISCUSSION

The differences in environmental impacts between WW production and DWS production are influenced by 2 key factors: removal of whey from the waste stream and disposal method used for the spent grain. The removal of whey from a landfill-destined waste stream reduces the CO₂e greenhouse gases by 6 t/10,000 L of whey according to WARM (EPA, 2016). The land-filling of spent grain produces approximately 1 t of CO₂e emissions. On the other hand, anaerobic digestion and composting produce no additional emissions. White whiskey required an additional 2 GJ of energy per 10,000 L batch due to the additional mashing step (Table 3). Energy use for each process was converted to mass of CO₂e using reported emissions factors for natural gas (EIA, 2016). The fermentation of WW produced more direct CO₂ than DWS (406 vs. 169 kg of CO₂e per 10,000 L of wash) due to the additional substrate available to the microbes from the mashing process.

Table 3. Calculated process differences of white whiskey (WW) and distilled whey spirit (DWS)

Production step	Energy input (GJ)		Output (kg)	
	WW	DWS	WW	DWS
Mashing (spent grains)	2.8	0.0	4,230	0
Fermentation (CO ₂)	—	—	407	169
Wash still distillation	9.5	10.1	—	—
Spirit still distillation (spent lees)	5.7	5.9	2,393	2,731
Total	18.0	16.0	7,030	2,900

However, the different masses of CO₂e emissions during fermentation and energy became negligible when examined from a functional unit perspective.

Ten thousand liters of wash produced more WW than DWS (1,792 vs. 628 bottles per batch). The total CO₂e emission per 10,000 L of wash processed is summarized in Table 4. The disparity between batch sizes requires examination at the functional unit level to understand the environmental impacts related to each process. To conduct an examination at a functional unit level, the total mass of CO₂e greenhouse gases produced per batch was divided the total number of bottles produced by each batch. A DWS batch produced a volume of spirit approximately one-third of that of the WW batch. To compensate for this batch size disparity, only 35% of greenhouse gases and water used per 10,000 L batch of WW were accounted to determine the environmental impact per bottle. Removal of whey from the landfill waste stream to produce DWS reduced net CO₂e emissions by 8 kg per bottle. In contrast, production of WW increased total net CO₂e emissions by approximately 0.45 kg per bottle. Thus, producing DWS instead of WW would reduce net CO₂e emissions by approximately 8.45 kg per bottle. Water inputs required for DWS production were 0.44 kg less per bottle than for WW production. This reduction was largely due to the elimination of the mashing step and differences in the required dilution to commercial spirit strength. This leads us to the apparent economic and environmental advantages of DWS production: a large resource sink is eliminated because no substrate preparation is necessary and whey is removed from a waste stream that otherwise produces CO₂e greenhouse gases.

The following assumptions are critical to the validity of these results: whey is removed from a landfill-type waste stream and DWS is produced instead of WW. The removal of whey from a waste stream is critical because it eliminates the production of CO₂e greenhouse gases associated with landfilling. The production assumptions for DWS are critical because this analysis compared the environmental impacts of DWS and WW based only on the differences in their production processes.

If these assumptions were true, DWS production would emit 8.4 kg less CO₂e greenhouse gases per bottle than WW production. Also, DWS production would use 0.44 kg less water than WW production. If the assumptions were not true; for example, if whey were generated solely for production of a potable spirit or if DWS would not replace another spirit in the marketplace, then the results of this study would not be valid.

The sensitivity analysis indicated that the parameter with the greatest impact on net CO₂e emissions was removal of whey from the landfill waste stream. After a 25% reduction in CO₂e emissions credit was applied to the removal from waste production step, net CO₂e emissions per bottle were recalculated, and the net reduction decreased from 8.4 to 6 kg of CO₂e per bottle. When this procedure was applied to the whey distillation process by increasing the amount of CO₂e emissions produced in the process by 25%, the net reduction of CO₂e only decreased from 8.4 to 8 kg per bottle. In the case where spent grain is sent to the landfill, this would be the single most impactful parameter associated with WW production. It should be noted that if the mashing, fermentation, and distilla-

Table 4. Carbon dioxide-equivalent (CO₂e) emissions produced during production processes

Production step	White whiskey (kg of CO ₂ e)	Distilled whey spirit (kg of CO ₂ e)
Removal from waste stream	—	−6,000
Mashing	138	—
Fermentation	406	169
Distillation	768	803
Landfilled spent grain	1,000	—
Total	2,312	−5,028

tion were considered a single process, then this process would have a greater effect on net CO₂e emissions than the landfilling of spent grain. This provides evidence that removal of whey from a landfill waste stream is the variable having the greatest impact in this process.

As seen in the LCA of WW production, one of the primary contributors to total CO₂e emissions was the disposal of spent grain from the mashing process. Although removing mashing significantly reduced the overall impact of DWS, attention is needed to other sources of bio-waste from every part of the distillation process. By using most of the available nutrient content of whey for fermentation, the remainder of the biological and chemical oxygen demand that has not been reduced is largely sequestered as biomass in the form of yeast. Significant work has been done on the treatment of distillery and brewery effluent (Butt, 1993; Fillaudeau et al., 2006; Devesa-Rey et al., 2011), focusing on yeast treatment for animal feed and fertilizer. Despite this earlier research, understanding the overall environmental impact of distillery effluent remains incomplete. Research into the true value of post-fermentation products is also necessary to fully assess the environmental and economic impacts of these processes.

Review of the production of WW and DWS has yielded valuable insights into the environmental implications for the artisanal cheese and craft distillation industries. The process-based LCA undertaken herein estimates that distillation of fermented whey can reduce systemic CO₂e emissions by 8.4 kg per 750 mL of DWS produced, while requiring 0.44 kg less water added into the production process compared with the production of WW, a similar clear, unaged spirit produced using malted barley. This analysis suggests that conversion to DWS is a more environmentally responsible approach than WW spirit production and whey disposal by landfilling. It should be noted that these conclusions apply to distilleries using a pot distillation system. As production of ethanol is scaled up, equipment used in the distillation process changes. Continuous distillation is often used for large-scale ethanol manufacture and has been applied to whey distillation on an industrial level in Ireland and New Zealand (Ling, 2008). The Carbery process has been used by a New Zealand company to produce over 18 million liters of ethanol annually. This process involves the use of continuous distillation equipment not examined in this study (Ling, 2008). Additional research would be required to examine the environmental impact of DWS produced in this manner.

Further research into the production of DWS as an environmentally friendly, value-added product is war-

ranted by craft distilleries and artisanal creameries. Besides lowering the environmental impact of whey disposal, DWS provides significant value-added potential for distilleries as the current craft spirit market expands. In particular, the production of DWS at the craft level may yield a beneficial partnership between a small, artisanal creamery desiring a sustainable means of whey disposal and a craft distillery seeking an economic advantage.

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