Comparative Cradle to Gate Life Cycle Assessment of 100% Barley-based Singha Lager Beer in Thailand

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Abstract
In this paper, the environmental impacts of lager brewing modeled after Singha's Pathum Thani Brewery process in Bangkok, Thailand were determined using life cycle assessment (LCA). The impacts studied assessed in this paper include global warming potential, eutrophication, and acidification. The potential for a rice adjunct was also analyzed to compare its impacts to those of a barley malt beer. Singha beer, which holds 58% of the Thai beer market, utilizes a 100% malt barley composition with the intention of preserving the original flavor and quality of their product (Euromonitor International, 2013). Other Thailand-based breweries utilize adjuncts as an alternative source of malting grain. The environmental comparison between the two scenarios was performed to include the cradle-to-gate process of beer production yielding 10 hectoliters of packaged beer. This LCA shows that rice cultivation dominates the environmental impacts for beer ingredients, but aluminum cans, regardless of which brew is being encased, bears the brunt of the environmental impacts within the scope of the study.

Graphical Abstract
See attached infographic

Keywords
Brewing, Environmental Impacts, Life Cycle Assessment (LCA), Barley

Abbreviations
AP: Terrestrial Acidification
FEP: Freshwater Eutrophication
FU: Functional Unit
GHG: Greenhouse Gas
GWP: Global Warming Potential
LY: Liquid Yeast
MEP: Marine Eutrophication
POFP: Photochemical Oxidant Formation

1. Introduction

Beer brewing incorporates markets from around the world. Hops from Germany, barley from Australia, corn from America and rice from Southeast Asia are some basic ingredients used to make numerous brews. Over the past 15 years, beer consumption has increased by approximately 4.5 liters per person worldwide (Basu, 2012). The market implications are apparent, and recent industry growth seems inevitable. With market growth comes an increase of associated outputs as well. For example, the UK's alcohol consumption now contributes to 1.5% of its total greenhouse gas emissions (Garnett, 2007). More regionally, beer production is an important industry in Thailand, with multiple large breweries operating daily to supply both domestic and international demand. The beverage industry makes up a significant portion of the Thai economy, as Thailand is the top alcohol-consuming country within the Association of Southeast Asian Nations, ASEAN (Thai PBS, 2014) at 1.9 billion liters consumed annually (Kirin Holdings, 2014). In fact, the most heavily consumed beverage in Thailand is beer, with Singha holding the largest share of the Thai beer market at 58% by volume (Euromonitor International, 2013). In this study, it is found that approximately 0.3% of Thailand's greenhouse gas emissions can be attributed to brewery processes.

As with any large industry, it is crucial to examine the effects of business on the environment and identify areas in which improvements can be made. In the brewing industry, environmental protection and profitability are interconnected, with companies constantly searching for methods of reducing water and resource consumption, energy use, and product loss. This drive towards sustainability is demonstrated in many companies' incorporation of methods to reuse both brewing ingredients and packaging materials and the use of efficient water treatment systems. By examining some of the methods employed by Singha's Pathum Thani Brewery, this study quantifies many of the environmental effects produced by beer brewing and identifies areas in which both the industry and consumers can reduce their environmental impacts. Singha's rival in beverage production, ThaiBev, has not only created a cheaper Thai (rice) beer called Chang that quickly took hold in the market, but also has a successful Carbon Footprint project of their business model and is the only Thai beer certified to have a product carbon footprint symbol (ThaiBev, 2013). In comparison, extensive analyses of Singha marketing have recently taken place, but no in depth study of the company's environmental impacts have been performed. Even with the company often publicly claiming their active participation in "environmental support groups" and a leader in "social responsibility", no direct LCA can currently be directly applied to Singha's brewery process. This LCA seeks to quantify the environmental impacts of brewing a barley beer such as Singha and comparing the process to that of a lager using rice adjuncts in addition to barley. This study will attempt to detail the differences in the two processes, identify high-impact areas, and explore scenarios for the cleaner production of beer (Sankrusme, 2013).

Relations with Singha were limited to a tour of the Pathum Thani Brewery and secondhand email correspondence with a Singha employee knowledgeable of the processes and inputs in question, with specific values that the tour could not provide. Regardless of the limited contact, the information provided by the company was instrumental in this LCA process as accurate energy inputs, recipe ratios, batch volumes and shipping specific to this brewery were given.

1.1 Goal

The goal of this study is to determine the environmental impacts of the production of Singha lager beer in a large scale brewing facility. The energy and resource-intensive processes of cultivating brewing inputs like barley and rice as well as producing yeast and malt suggest significant environmental impacts such as GWP and Acidification that can be directly attributed to the industry. This has not been studied in depth in Thailand, nor has the comparison of barley to barley-based adjunct beer been made nationally. By considering the resource use and emissions produced from beer brewing beginning with the growth of ingredients such as hops, yeast, and barley and ending with bottling, the environmental effects of beer production can be quantified. The intended audience of this Life Cycle Assessment (LCA) includes researchers, producers, and environmentally conscious consumers. The results can be used to identify which steps in the beer production process have the largest impacts on environmental health, but cannot be used to examine the production of other alcohols such as wine or spirits or beer produced on a smaller scale, such as craft brewing. The study is limited geographically to areas in which Singha is produced, and is relevant until major changes occur in any of the production steps. The LCA conducted is in accordance with ISO standards and follows the beer production process from cradle to gate.

1.2 Scope

The scope of this study is to follow the production of Singha beer produced in the Pathum Thani Brewing Facility by measuring the inputs, emissions, and energy use that go into overall production. This includes agricultural processes, chemical inputs and land use, all of the necessary transportation, and the complete brewing and bottling process. The environmental impacts of glass versus aluminum cans is discussed, and while their recyclability is accounted for, the process of consumption and community recycling is excluded. Excluded are the initial inputs and environmental costs of starting a brewery, including capital equipment and maintenance, and transport of employees to the brewery. The gate to grave is excluded due to lack of reliable data and the variability among consumers.

The studied product system is that of brewing 100% malted barley beer at 5% alcohol by volume (ABV). The conventional brewing process is outlined in Figure 1. The main ingredients are malt, hops, and water. A specific strain of yeast helps determine the unique taste of the brew and produces ethanol and CO_2. Malt used at Pathum Thani and Boon Rawd breweries for Singha beer is made of 100% barley with no adjuncts, which is an important part of their business model. The addition of a rice adjunct is considered in this study to show the environmental association of adding adjuncts to malt barley beer.

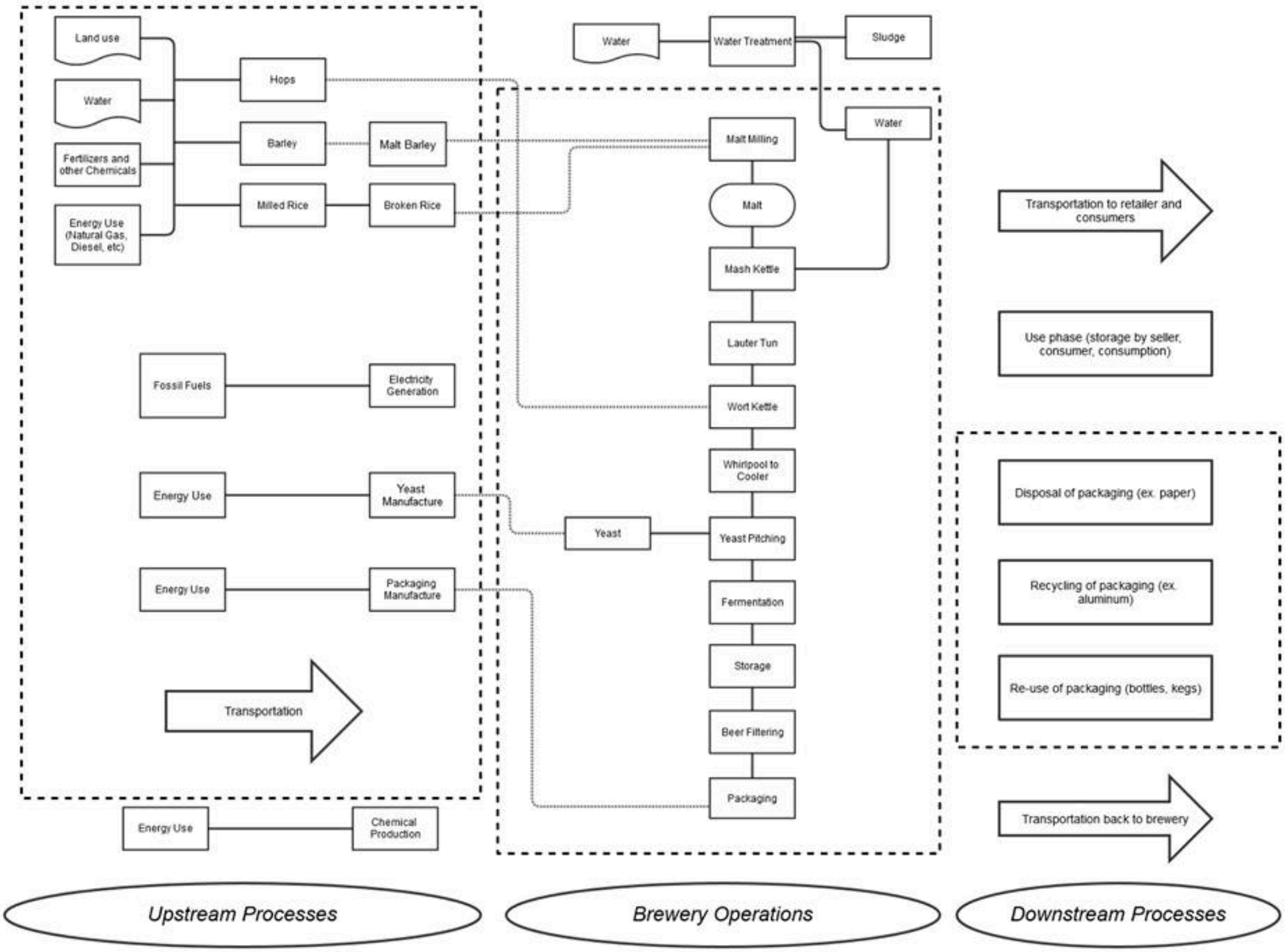
1.3 Functional Unit & Environmental System Boundary

The functional unit used in the study is the production of 10 hectoliters (1,000 liters) of Lager beer, a malt barley based beer with a 5% ABV content. The glass bottle size selected is 330 mL, which is packed 24 bottles per box for distribution. Per FU, 3030 glass bottles and 126 boxes are needed. The aluminum can selected is 355 mL, and a keg which holds draft beer was also compared, with a size of 59 liters. 2,817 aluminum cans and 17 kegs are needed per FU.. The glass bottle size of 330 mL was selected as it is a standard size for beer in glass bottles. All other beers produced in Thailand, including Chang, are bottled in this size, making a direct comparison simple. Singha also sells 500 mL bottles, but its competitors in Thailand sell 630 mL bottles. The aluminum can and keg volumes are standard volumes globally. The functional unit of 1000 L of beer is also consistent with many other studies of this kind. To put this value in perspective from a consumer's point of view, 1000 L of beer is equivalent to 13 average Americans' annual beer consumption (Kirin Holdings, 2012).

The environmental burdens from the production of capital goods used in agricultural processes and in the brewing facility will be excluded in this study. The distribution of the final product will also be excluded, as this study was conducted with a Cradle-to-Gate intention. However, the transportation of ingredients to the production facility and the production of agricultural inputs such as barley, hops and yeast will be included.

Figure 1 shows the basic process flow diagram of this study and maps which processes are included and excluded for the scope.

Figure 1



Processes involved in Singha beer production included and excluded from scope

1.4 Allocation Methods

Economic allocation was used to calculate emissions from a rice adjunct, as broken rice, a by-product of rice milling,was the assumed ingredient. A 30% broken rice composition was chosen based on the recipe used by Anheuser-Busch to brew Budweiser, a 5% ABV lager.

Allocation for the byproduct of mash, or spent brewer's grains, was performed by the displacement method. The spent grains are used as a source of animal feed and therefore are credited for impacts of the feedstock that they are replacing.

1.5 Data Sources and Quality

The majority of data used for this life cycle assessment were obtained from secondary sources. Some data were provided by the facility visit and communications with Pathum Thani Brewery. Data specific to Thailand were used where applicable, but in some cases data with a focus on other countries was adapted to our purposes. A summary of the data sources used for different processes is shown in Table 1. Locations of access are identified in the table as well.

Table 1: Data sources

Data category	Title	Authors	Year	Publisher	Access	Country of Origin/Focus
Barley cultivation and Malting	LCA Case Study Western Australian Grain Products	Narayamaswamy, Altham, Berkel, McGregor	2004	Curtain University of Technology	Online at iere.org	Australia
	Estimating Annual Irrigation Requirements	Callow, Kenman, Walker, Warren	2006	Queensland Government	Online at dairyinfo.biz	Australia
	Comparative LCA of Malt-Based Beer and 100% Barley Beer	Kløverpris , Nielsen, Ratzel	2009	Novozymes	Online at novoenzymes	Denmark
Rice Cultivation	Life Cycle Assessment of Milled Rice Production in Thailand	Kasmaprupet, Paengjuneuk, Saikhwan, Phungrassami	2009	European Journal of Scientific Research	Published Online	Thailand
	Eco-Efficiency of Paddy Rice in NE Thailand	Thanawong, Perret, Basset-Mens	2013	Journal of Cleaner Production	Published Online in ScienceDirect Database	Thailand
	Water Management: Rice in Asia	Facon	2013	FAO	Online at FAO.org	Thailand
Hops	Environmental Impacts of Food Production and Consumption	Foster, Green, Dewick, Evans, Flynn, Mylan	2006	Defra	Online at ifr.ac.uk	United Kingdom
Yeast	Carbon Footprint of Yeast Production	COFALEC	2012	COFALEC	Online at COFALEC.com	European Union
Brewery Operations	Pathum Thani Brewery	Tour	2014	-	-	Thailand

	Information					
Electricity	Electricity in Thailand	-	2009	Simapro7.3	Simapro7.3	Thailand
Spent Grain Allocation	Environmental Systems Analysis of Pig Production - The Impact of Feed Choice	Eriksson, Elmquist, Stern, Nybrant	2005	Swedish University of Agricultural Sciences	Online in SpringerLink database	Sweden
Packaging	Life Cycle Impact Assessment of Aluminum Beverage Cans	PE Americas	2010	PE Americas	Online at aluminum.org	USA
	Life Cycle Assessment of Container Glass	AIGMF	2012	AIGMF	Online at AIGMF.com	India
	Life Cycle Assessment of Paperboard Packaging Produced in Thailand	Ongmongkolkul, Nielsen, Nazhad	2002	Asian Institute of Technology	Online at AIS.edu	Thailand
	Life Cycle of Beer in Support of Environmental Product Declaration	Lalonde, Nicholson, Schenck	2013	Earthsure	Online at iere.org	USA
Transportation	2012 Guidelines of Defra/GHG Conversion Factors Company Reporting	Hill, Walter, Choudrie, James	2012	Department of Energy and Climate UK Government	Online at gov.uk	United Kingdom
	Lorry Sizes and Weights	Butcher	2009	House of Commons Library	Online at parliament.uk	United Kingdom

1.6 Impact Methodology

ReCiPe is the impact methodology used in this study. Impact categories were selected based on relevance, degree of impact, and data availability. Categories discussed in this study include global warming potential, acidification, eutrophication, water use, land use, and energy use.

1.7 Assumptions and Limitations

Limitations of this study include the lack of information access to the particular brewing process being studied. Pathum Thani Brewery graciously allowed for a tour of the plant to take place and gave as much information possible regarding energy inputs and the recycling process, but exact input ratios were unavailable. Because of this, recipes for similar brews were considered and a reasonable input ratio for each ingredient in question was decided upon. Exact water emissions were outside of the scope of this study, but water treatment options are discussed in the conclusion of the paper.

2. Methods

Many inputs come together to produce the signature lager beer of Singha Brewing. Barley is instrumental in the process, as the malt it produces is an integral part of the Singha brewing model. No adjuncts are utilized in their brewing process. Rice is incorporated in this study in order to examine the idea of a rice adjunct to the malt barley brew. This was done to show how the addition of rice that is produced in Thailand could change the emissions of Pathum Thani Brewery if incorporated. Other Thai breweries use this recipe, so a market does exist for both brews.

In conventionally brewed malt barley beer, the malted barley is ground into grist and combined with water to break down the natural starches into fermentable sugars. The liquid and mash are then separated and the liquid, now called wort, is boiled in the presence of hops. The spent grains are used in animal feeds. Next the hot wort is allowed to settle, and the spent grains are again removed and sold as animal feed. The remaining wort is cooled and pitched, meaning yeast is added to begin the essential fermentation process. This breaks the sugars down into alcohol and CO_2. When the desired CO_2 and alcohol content is achieved, fermentation is halted. The young beer is allowed to mature, and the yeast is reclaimed for reuse. The matured beer is then sold to consumers across the nation and world in different sized glass bottles and aluminum cans.

2.1 Barley

Malted barley makes up the entire grain source of Singha beer. The company prides itself on only brewing from one grain without any adjuncts. The barley is malted and shipped from Australia. The main territory for malt barley production is Western Australia, which is known as the wheatbelt region.

2.1.1 Cultivation

Barley cultivation has occurred for thousands of years. There are two main types of barley, 2-row and 6-row barley. While 2-row barley is lower in protein content and largely used in German beers, 6-row barley is high in protein which is useful for animal feed as well as for making malt meant for lager-styled beers (Johnston et al., 2009). A study from Australian dairy farmers addresses the irrigation demands for barley silage, or feed barley. Because it is feed barley, one can infer that it is then 6-row barley and is comparable to the water demands of 6-row malting barley. The study calculates expected rainfall to determine the amount of irrigation water necessary to cultivate barley, which is about 1,200,000 L per hectare per crop(Callow et al., 2006). Barley cultivation data were found within a Western Australian Grain Belt study (Narayanaswamy et al, 2004), which is where Singha's barley in imported from, making these data as relevant as possible to our particular case study. These values can be seen in Table 2 below.

Table 2: Inputs and emissions from barley cultivation in Western Australia

Resources	Units	Value
land use	Ha	0.0630
sylvinite (~ 30% KCl)	kg	2.533
phosphate (ore)	kg	6.784
Irrigation Water*	L	75600
Materials/Fuels		
Barley Seeds	kg	8.435
Automotive Diesel	kg	0.724
Ammonia	kg	0.472
CO_2	kg	0.621
Sulphuric acid	kg	1.384
Energy and Natural gas	GJ	0.0428
Steam	kg	0.695
Steam Energy	MJ	2.44
Electricity/Heat		
Tractor rural (MJ input)	MJ	219.10
Electricity from WA coal	kWh	1.165
Energy from natural gas	MJ	5.683
energy from petroleum	MJ	0.357
Emissions to Air		
methane (rural)	kg	0.0181
N_2O	kg	0.095
NO_x	kg	0.0184
CO_2 (fossil)	kg	7.439
SO_2	kg	0.0144
Ammonia	kg	0.000624
Urea	kg	0.000621
VOC	kg	0.0372
CO	kg	0.163
Emissions to Water		
Nitrogen	kg	0.00194
Pesticides	kg	2.71E-05
Emissions to Soil		
Pesticides	kg	0.00652
Phosphorous (agr.)	kg	0.458
Harvested		
Barley	tonne	0.14

Barley	kg	127.2

** Irrigation Water value is calculated from the separate study of "Estimating Annual Irrigation Water Requirements" (Callow et al., 2006).*

2.1.2 Malting

A barley-to-malt ratio was found of 1.22:1 (Kløverpris et al., 2009). This ratio was utilized to allow Table 2 to be in terms of the functional unit. The co-products of barley sharps and malt sprouts are put through allocation by mass to allow for more true input values for an exclusively malt output. They are used in animal feed and have a high energy content, making them valuable. However, their mass compared to malt is slight, making the allocation to malt have a factor of 0.94.

Table 3: Input and output materials for malting process of barley

	Material	Unit	per FU	Allocation to Malt per FU
Inputs	Barley	kg	135.1	127.2
	Water	L	248.9	234.3
	Electricity	kWh	10.66	10.04
	Natural Gas	Nm^3	6.832	6.43
Output	Malt	kg	110.7	110.7
	Barley Sharps	kg	1.51	---
	Malt Sprouts	kg	5.36	---

adapted from Kløverpris et.al 2009

2.1.3 Transportation

The distance of malt barley transportation is assumed to be 125 km, the average transportation distance found for the Western Australian region and malt product (Narayanaswamy et al, 2004). A standard wedge trailer is assumed (YRC Freight, n.d.) with standard capacity and load (Butcher, 2009). Malt barley bulk density was found to calculate the maximum load of the trailer (The Engineering Toolbox, n.d.). Tonnes of diesel consumed were calculated based on distance and an average fuel consumption rate of 6 mpg with a full load and 8 mpg empty (DeMorro, 2014). This was then translated into kg CO_2 eq by using the emissions of CO_2, CH_4, and N_2O for diesel and ReCiPe midpoints (DECC, 2012). Pathum Thani Brewery reported a volume of 20% tank capacity by volume of malt barley in the mash kettle, which yields 110.7 kg per functional unit of 10 hL. Based on the unit process amount of input malt barley, the functional unit kg CO_2 eq was calculated for land transportation in Australia, and came to be 0.493 kg CO_2 eq.

The malt barley is then shipped from a western port, Geraldton, to Laem Chabang, Thailand. (Sea Route, n.d.). A 40 foot dry storage container (World Shipping Council, 2014), a 7500 TEU Post-Panamax (World Shipping Council, 2013), and an average speed of 22 knots (USMARAD, n.d.) were assumed for sea transport. Using the malt barley density, the height of the grain inside each container could be calculated (Shipping Australia, 2012), and the volume per ship then concluded. The time at sea used in calculations (Sea Route, n.d.) was 6.3 days and time at port was two days (Kahveci, 2001). This combined with average fuel consumption at sea and port (Palgrave MacMillan, n.d.) led to tonnes of diesel consumed for the one-way trip, assuming that the return trip will be full of Australian imports and not within the scope. Using the aforementioned diesel emission factors, the functional unit of carbon dioxide emissions was calculated to be 2.98 kg CO_2 eq for the sea transportation of malt barley.

Regarding transport from Port Laem Chabang to Pathum Thani Brewery in Bangkok, the same transportation means are assumed from Australian transport, but with a distance of 133 km according to Google Earth. This new diesel consumption value was translated again into emission factors and then found to be 0.525 kg CO_2 eq. The total transportation CO_2 equivalence for malt barley is shown in the table below, where WA stands for the Western Australian region.

Table 4: Total transportation kg CO_2 equivalent for Barley

Transport	City Names	kg CO_2 eq	kg CO_2 eq per FU
WA to Port	WA, Geraldton	227.64	0.493
Australian Port to Thai Port	Geraldton, Laem Chabang	3044349	2.9778
Port to Brewery	Laem Chabang, Bangkok	242.2	0.525
Total		4.00	

The methane and nitrous oxide also emitted from diesel and incorporated into the above GWP calculation can also be taken to show their potential impacts in other impact categories of acidification, photo-oxidant formation, and nutrient enrichment. Below, Table 5 shows the total impact values of each category.

Table 5: Impact category values for barley transportation per functional unit

		GWP	AP	POFP	NEP
Molecule	**kg gas per FU**	**kg CO_2 eq**	**kg SO_2 eq**	**kg NMVOC**	**kg N eq**
CO_2	3.966	4.0	-----	-----	----
CH_4	5.515E-5	0.00138	-----	5.6E-7	----
N_2O	9.5E-5	0.0285	0.0159	-----	3.724E-6
Total	3.996	0.0159	5.57E-7	3.724E-6	

This total GWP emission value is comparable to the amount of CO_2 produced by one Thai commuter in a day.

2.2 Hops

Hops are a necessary addition to beer brewing, as they balance the taste, contribute to preservation, and add aroma and bitterness to the beer. Singha imports their hops from Germany, where a third of land dedicated to hops production is located (EC, 2014). The region of Hallertau is most dense for cultivation, and this region is used as a reference point for cultivation and for transport. The standard amount of hops to add to 10 hL of beer is 1.45 kg (Lalonde, 2013).

2.2.1 Cultivation

Currently, there are no life cycle assessment papers published regarding hops cultivation. However, it is agreed upon that hops production has a high environmental impact on the land used (Crnivec et al., 2007). Lack of data quantification of impacts difficult, but it was found that 9.85 kg of CO_2 emissions per kg of hops are emitted (Foster et al., 2006). In terms of the functional unit, 1.45 kg of hops is put into the brewing process, resulting in 14.3 kg CO_2 per functional unit. This is equivalent to the CO_2 emissions from using a light bulb for 16 months (Carbon Footprint, n.d.).

2.2.2 Transportation

Hersbruck Germany is used for exact transportation distance values. This is a main town in the Hallertau region for cultivating and shipping hops. The companies ship out of Port Hamburg, located 632 km by road from the area of cultivation. The miles per gallon of a wedge trailer as stated in section 2.1.3 is again assumed and all trailer and sea transport assumptions were confirmed by the Barth Haas Group, a hops export company located in Hersbruck. The hops are shipped in pellet form. The sea distance and days at sea is calculated again using the online resource mentioned in 2.1.3, and the distance from Port Laem Chabang to the brewery is seen to be 146 km. These values combined with hops average density (Lenahan, 2009), diesel consumption rates, and aforementioned emission factors resulted in the values seen below in Table 6.

Table 6: Total transportation kg CO_2 equivalent

Transport	City Names	kg CO_2 eq	kg CO_2 eq per FU
Producer to Port	Hersbruck, Hamsburg	1150.95	0.03793
German Port to Thai Port	Hamsburg, Chaem Labang	9499644	0.177
Port to Brewery	Chaem Labang, Bangkok	265.89	0.00876
Total			0.223

Acidification, photo-oxidant formation, and nutrient enrichment are again calculated for hops transportation and shown below in Table 7.

Table 7: Impact category values for transportation of hops per functional unit

		GWP	AP	POFP	NEP
Molecule	**kg gas per FU total**	**kg CO_2 eq**	**kg SO_2 eq**	**kg NMVOC**	**kg N eq**
CO_2	0.22168	0.2	-----	-----	----
CH_4	3.08E-6	0.00008	-----	3.0E-8	----
N_2O	5.34E-6	0.00159	3.0E-6	-----	2.08E-7
Total	0.223	3.0E-6	3.0E-8	2.08E-7	

2.3 Yeast

Yeast is instrumental to the beer brewing process, as it allows for fermentation of the wort to take place and produces ethanol and CO_2. Lagers such as Singha employ bottom-fermenting yeast, saccharomyces uvarum, which is best used at temperatures between 7 and 15 degrees Celsius. Bottom-fermenting yeasts develop more slowly than top-fermenting yeasts, and tend to settle at the bottom of the fermentation tank towards the end of the process. Aside from producing ethanol, fermentation contributes to the flavor and coloring of the beer by producing numerous other chemical compounds such as acetaldehyde and dimethyl sulfide (BeerAdvocate, 2014). Yeast can be reused multiple times if washed properly after being removed from the fermentation tank. Yeast is assumed to be used twenty times in this study for the purposes of production and transportation allocation (Huuskonen et al., 2010). The yeast that Singha uses is imported from Germany.

2.3.1 Production

A weighted average yeast density was calculated (Andrea et al, 2009) based on the fact that the liquid yeast (LY) used by Singha is 18% dry matter by mass (COFALEC, 2012). For liquid yeast, the g CO_2 eq emissions were adapted from an LCA on European yeast production (COFALEC, 2012). Singha uses approximately 4,000 L of liquid yeast per batch. These calculated values can be seen in Table 8. A twenty times reuse value is used for the allocation process below. This is done because that yeast is reused 20x in the brewing process so allocation more appropriately represents the associated emissions by dividing them by twenty.

Table 8: Liquid yeast production GWP per functional unit with allocation

	Unit	**Value**
Liquid Yeast per Batch	L	4000
CO_2 eq per kg Liquid Yeast	g	363
Liquid Yeast Average Density	kg/m^3	1020.9
CO_2 eq per 88,000 L beer (1 Batch)	kg	1482.4
CO_2 eq per FU with Allocation	kg	0.842

2.3.2 Transportation

Bonn, a region in Germany with a high density of yeast exporters (Radermacher, n.d.), is assumed for this study. The closest port is Port Leer, which is also assumed. The distance to this port is 316 km, and the same truck transport assumptions mentioned in 2.1.3 are used to calculate the tonnes of diesel per trip. Utilizing the aforementioned emission factors, the kg CO_2 eq value for German land transport is calculated. This is done in terms of the functional unit. In order to find the functional unit mass, a weighted average of yeast density (Andrea et al., 2009) is derived based on the fact that liquid yeast holds 18% dry matter yeast and 82% water (COFALEC, 2012). Singha claimed that 4,000 L of liquid yeast were used per production of 88,000 L of beer, and this was scaled down to the 10 hL functional unit to calculate the mass. The kg CO_2 eq is calculated to be 0.61 for German land transport of yeast.

Sea transport from Port Leer to Port Laem Chabang takes 19.5 days (Sea Route), and the same container ship volume and type assumed in 2.1.3 is maintained here. This allows for the total tonnes of diesel per trip to be calculated (DeMorro, 2014), producing a GWP of 2.83 kg CO_2 eq for yeast sea transport.

Regarding land transport within Thailand from Laem Chabang to Pathum Thani Brewery, the distance, mode of transportation and diesel emission factors are assumed the same as aforementioned. This results in a GWP of 0.2554 kg CO_2 eq. The summary of these results is seen in Table 9, including the allocation for yeast reuse.

Table 9: Total transportation kg CO_2 equivalent for yeast in terms of 10 hL functional unit including reuse allocation

Transport	City Names	kg CO_2 eq	kg CO_2 eq per FU	kg CO_2 eq per FU with allocation
Germany: Land to Sea	Bonn, Leer	575.48	0.61	0.03034
German Port to Thai Port	Leer, Laem Chabang	9356193	2.8	0.14
Thailand: Port to Brewery	Laem Chabang, Bangkok	242.21	0.2554	0.01277
	Total	9357011	3.70	0.2

Acidification, photo-oxidant formation, and nutrient enrichment are again calculated for yeast transportation and shown below in Table 10.

Table 10: Impact category values for yeast transportation per functional unit

		GWP	**AP**	**POFP**	**NEP**
Molecule	**kg of gas per FU**	**kg CO_2 eq**	**kg SO_2 eq**	**kg NMVOC**	**kg N eq**
CO_2	3.6421	3.6	-----	-----	----
CH_4	5.065E-5	0.00127	-----	5.12E-7	----
N_2O	8.77E-5	0.02613	4.9E-5	-----	3.42E-6
Total	3.670	4.9E-5	5.12E-7	3.42E-6	

2.4 Rice

Mainly cultivated within Southeast Asia, rice has been a food staple for centuries. Rice is Thailand's 6th greatest export (Simoes, n.d.), and the country holds the greatest share of rice exports in the world in terms of value with over 29 million acres dedicated to the industry (GPRD, 2014). The ease of obtaining rice within Thailand formed the basis of the idea that a beer produced with an adjunct of rice could result in significantly lower emissions. Rice is the second largest adjunct material used within the brewing industry and is regarded by some as desirable because it does not interfere with the basic malt character of the beer (Beer Advocate, n.d.). A ratio of 30% rice, 70% malt input was used for this study under the notion that Anheuser-Busch utilizes this ratio in America, producing a very similar recipe and taste to Singha Lager (Princeton, n.d.).

The functional unit of rice was determined using the mass for 100% malt beer brewed by Singha. This 110.7 kg was manipulated to determine the mass of a 30% rice, 70% malt beverage. Thus, 33.21 kg of rice would be used for a 10 hL beer batch.

Jasmine rice was chosen as the adjunct, because it is widely grown within Thailand and is considered the highest quality Thai rice (STC Group, 2011). With high quality grains, the broken rice grains are actively separated from long grain and sold separately. Broken rice is utilized for beer production because it is cheaper than long grain rice NIIR, n.d.). Chai Udom Rice Mill Factory Co., Ltd. was chosen to represent standard jasmine rice processing, and were contacted directly to receive the transportation information utilized below. This company is located within the largest production region of jasmine rice (Jasmine Rice Exporter, 2010) and was extremely responsive to inquiries made.

2.4.1 Cultivation

A case study of milled rice production in Thailand provided much of the information regarding the environmental impacts of rice cultivation. The study, conducted by Thammasat University (Kasmaprapruet et al., 2009), follows the rice production process from seeding to milling, and assumes a paddy transportation distance of 50 kilometers. According to data from the study, cultivation contributes to 95% of the total global warming potential of the rice production chain. Also significant is the energy-intensive process of drying, which consumes 55% of the total energy used in the production steps. The study shows that the total environmental impacts associated with rice production in Thailand (per kilogram of rice) are 2.927 kg CO_2 eq, 3.187 g SO_2 eq, and 12.90 g N eq, for the impact categories of GWP, acidification, and eutrophication, respectively (Kasmaprapruet et al., 2009). Based on the fact that Thailand exports approximately 10 billion tonnes of rice annually (Index Mundi, 2014), the fuel combustion carbon dioxide emissions from rice cultivation was 363 g per functional unit (which is the largest CO_2 provider during cultivation), and that Thailand's greenhouse gas emissions in 2012 were 0.26 billion tonnes of CO_2 (Olivier et al, 2013), rice cultivation accounts for approximately 42% of these national emissions.

After adjusting the functional unit to 10 hL of beer (using a ratio of 30% rice and 70% barley), 33.21 kg of rice produces 97.20 kg CO_2 eq, 0.106 kg SO_2 eq, and 0.428 kg N eq. Land use values were based on average rice production values from irrigated fields in Northeastern Thailand and were shown to be 0.013 hectares per FU (Thanawong et al., 2013). Water use values were taken from a Food and Agriculture Organization of the United Nations (FAO) study and were determined to be much higher than water use impacts from barley cultivation, at 132,840 L per FU before allocation (Facon, 2013). These numbers show that rice production is a significant contributor to many impact categories. Much of this is due to the high levels of methane released during cultivation. However, for this study economic allocation will be used to account for the fact that broken rice (not long grain) is the assumed adjunct. Current market prices for the byproducts of rice milling (broken rice (440 USD/mt), long grain jasmine rice (1050 USD/mt), rice husk (47.22 USD/mt), and rice bran (314.81 USD/mt) were used to find that broken rice should be attributed 13% of the total rice emissions. The percentage by mass of each byproduct is shown below in Figure 2. Table 11 summarizes the above information and allows for the value per functional unit to be determined. Values after allocation are displayed below in Table 12.

Figure 2: Percentage of Rice Milling Byproducts by Mass

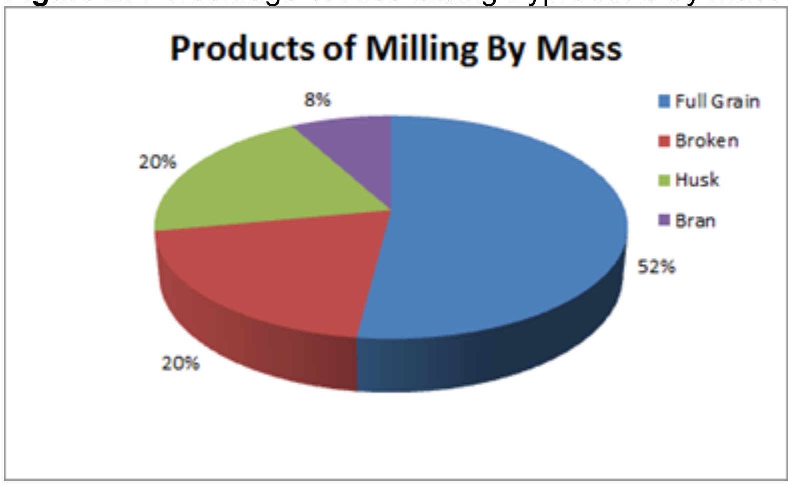


Table 11: Values of broken rice for economic allocation

Economic Allocation Rice	Value (USD)
Market Price Broken Rice	440 per tonnne*
Market Price Long Grain Jasmine Rice	1050 per tonne*
Market Price Rice Husk	47.22 per tonne
Market Price Rice Bran	314.81 per tonne
Per FU Broken	14.61

(Y Charts, 2014)
(Export, 2014)

Table 12: Broken rice economic allocation of impacts

Impact Category	Units	per FU Rice	Broken Rice After Allocation*
GWP	kg CO_2 eq	97.2	33.26
Acidification	kg SO_2 eq	0.106	0.0362
Eutrophication	kg N eq	0.428	0.147
Land Use	ha	0.013	0.004
Water Use	L	132840	45451.81

**Allocation values were determined economically by multiplying impact values by 0.13.*

When taking the market price of Australian barley at 250 USD/mt and adjusting to the functional unit, monetary values for 100% and 70% barley usage can be calculated. These values are compared below in Table 13.

Table 13: Economic comparison of 100% barley versus 70% barley and 30% broken rice brew composition

Cost of Crop	Value without Rice	Value with Broken Rice
Market Price (USD/mt)	250	402.6
Cost 100% barley (USD/FU)	31.80	-
Cost 70% barley (USD/FU)	22.26	36.87

An economic comparison reveals that malt with a 30% broken rice adjunct results in a more expensive product per functional unit. This is because broken rice still carries a higher market value than Australian barley (440 USD/mt to 250 USD/mt). The same economic indicators were used to allocate for broken rice emissions. The emissions from barley production were taken at 70% of their 100% values and summed with allocated broken rice emissions. The results are displayed below.

Table 14: Impact category values for 100% barley versus 70% barley and 30% rice brew composition

Emission Category	Units	100% Barley	70% Barley + 30% Rice
GWP	kg CO_2 eq	41.84	62.55
Acidification	kg SO_2 eq	0.07944	0.092
Eutrophication	kg N eq	6.42E-03	0.151
Land Use	ha	0.0630	0.049
Water Use	L	75596.1	98369.1

2.4.2 Transportation

Chai Udom Rice Mill Factory stated that the average distance from farm to processing is 11 km, and the truck can hold 15 tonnes of rice. The company also said that 20% of the rice brought to processing is broken rice. The diesel consumption per trip was calculated based on full and empty truck loads, assuming the standard gas mileage aforementioned in section 2.1.3. The resultant GWP emissions are shown below in Table 15.

Table 15: GWP for transportation of jasmine rice from cultivation to processing, including broken rice allocation

Molecule	kg of gas per FU	kg CO_2 eq per tonne	kg CO_2 eq
CO_2	3.98	3164	19.9
CH_4	0.00006	1.1	0.00691
N_2O	0.00010	22.7	0.143
		Total	20.04
		FU	0.044

From the processing plant to Bangkok it is approximately 480 km with the same truck capacity but exclusively carrying broken jasmine rice, thus needing no allocation of load. This GWP can be seen below in Table 16.

Table 16: GWP for transportation of broken jasmine rice from processing to Bangkok

Molecule	kg CO_2 eq per tonne	kg CO_2 eq
CO_2	3164	867.9
CH_4	1.1	0.30
N_2O	22.7	6.23
	Total	874.4
	FU	1.94

The total GWP for rice transportation to the brewery is approximately 1.98 kg CO_2 eq per 1000 L beer brewed.

Acidification, photo-oxidant formation, and nutrient enrichment are also calculated for total broken rice transportation and shown below in Table 17.

Table 17: Impact category values for broken rice transportation per functional unit

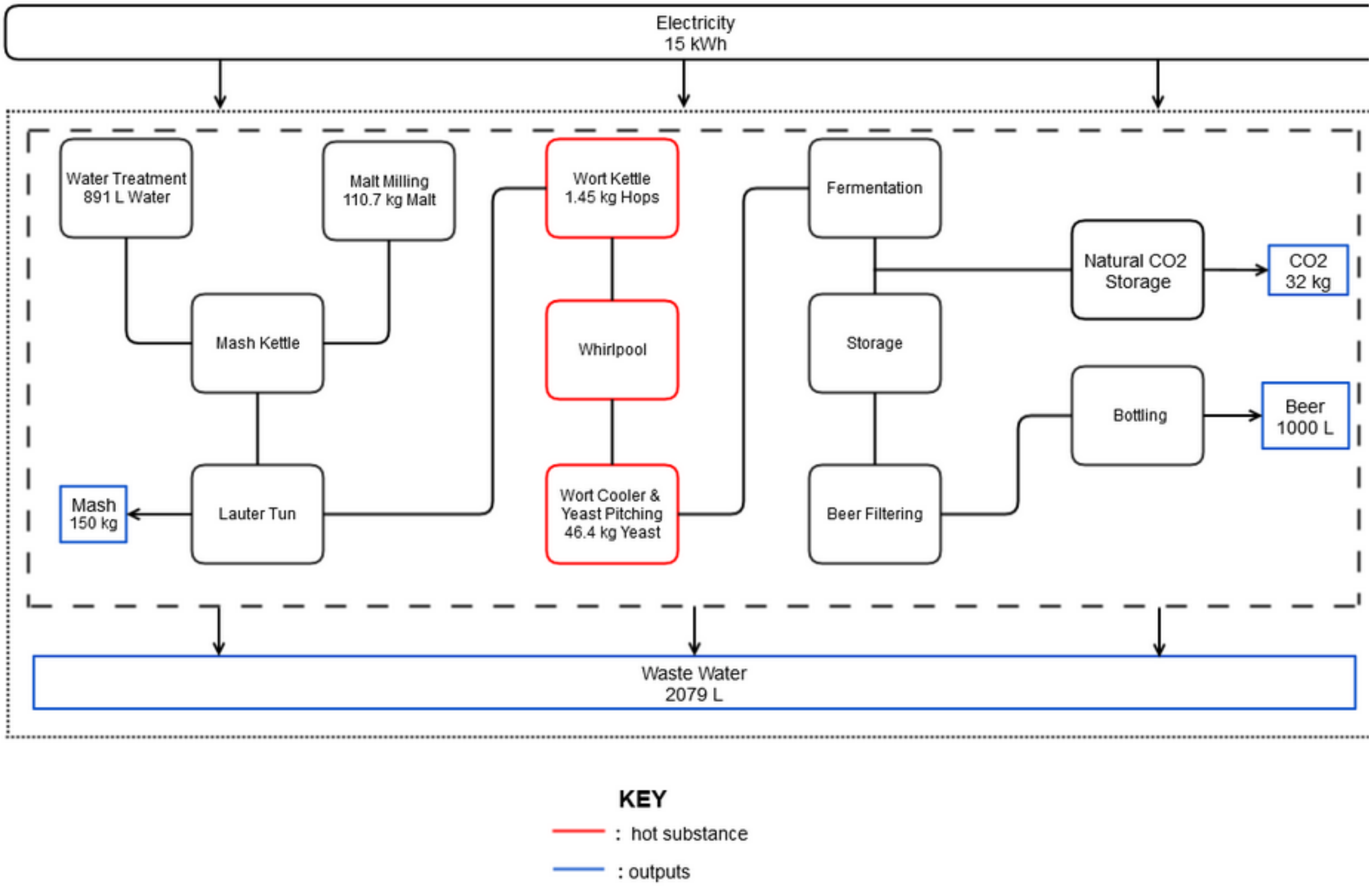
		GWP	AP	POFP	NEP
Molecule	**kg gas per FU**	**kgCO_2eq**	**kg SO_2 eq**	**kg NMVOC**	**kg N eq**
CO_2	1.911	1.96	-----	-----	----
CH_4	2.65E-5	0.00066	-----	2.7E-7	----
N_2O	4.60E-5	0.0137	2.58E-5	-----	1.794E-6
Total	1.98	2.58E-5	2.7E-7	1.794E-6	

2.5 Beer

Beer production is now a universal process that is fairly standard. The unit process shown in Figure 2 is specific to Pathum Thani Brewery, as taken from their website and modified for simplicity (SinghaCorporation, n.d.). Below, each process is elaborated upon to add clarity to the brewing process.

2.5.1 Brewing

Figure 2



Unit process map of Singha brewing process in terms of 10 hL functional unit

Input Water Treatment
Pathum Thani brewery uses water from the Chao Phraya in their operations, as they are located along its banks. This water is filtered using sand and other methods.

Malt Milling
Malt grain kept in a silo is passed through the milling process to produce a fine malt grist. Malt to water input ratio is 2:8 by volume. The process of beer production within the facility has a 10% loss by volume, so to achieve 88,000 L per batch approximately 98,000 L of water and malt grist are initially combined. Using this given ratio, 891 L of water and 110.7 kg of malt are combined in the mash kettle per the 10 hL functional unit. According to hammer milling data from a study on lager beer production, malt milling releases a large amount of CO_2 eq emissions and has a relatively high electricity use (Kløverpris et al., 2009).

Mash Kettle

Hot water and the fine malt grist are mixed together in a mash kettle under controlled temperature to produce fermentable sugar. By hydrating and heating the barley, the enzymes in the grain are activated and begin making fermentable sugar. The brewer can adjust the temperature and pH to control which enzymes are activated, thereby affecting the wort consistency and flavors. The starches in mash become fully saturated at 65 degrees Celsius (Palmer, 1999).

Lauter Tun
The mash which was converted to sugar is transferred into the lauter tun, where liquid is separated from the mash. The resulting liquid is called wort. There is approximately 0.15 kg of mash product produced per L of beer (Karjalainen, 2013), so 150 kg are removed per functional unit.

The mash that is separated from the remaining liquid in the lauter tun is a byproduct used in the livestock industry as feed material. This byproduct, also known as spent brewer's grains, was allocated using the displacement method. Spent grains used in livestock feed displace other sources that would cause environmental impacts in their cultivation and processing, and can therefore be credited for the environmental impacts avoided by inclusion of the spent grains. In Thailand the swine industry is sizable, and the spent grains from beer production can be included in pig feed. Spent brewer's grains are high in protein and can be used at a rate of 20% of feed for juveniles and higher rates for finishing pigs and sows (Aguilera-Soto et.al., 2009). The spent grains were credited for displacing soybean meal. There is approximately 0.15 kg of mash product produced per L of beer (Karjalainen, 2013), so 150 kg are removed per functional unit. Therefore, 150 kg of soybean meal will be credited for the functional unit. The credits are shown in Table 18.

Table 18: Mass allocation of co-products from lager beer production

Feedstock	GWP (kg CO_2 eq) for 150 kg of feed	Acidification (g SO_2 eq) for 150 kg of feed
Soybean Meal	109.5	1246.5

Adapted from Eriksson et. al, 2005

Wort Kettle
Wort is transferred to the wort kettle to be boiled for 60-90 minutes at 80-90C. Hops are added during this stage.

Whirlpool to Wort Cooler
The hot wort is separated in a whirlpool (hops go to bottom), the remaining wort is transferred to the cooler.

Yeast Pitching
Sterile air and yeast are added to the cooled wort.

Fermentation
The mixture is transferred to a tank for 7-10 days for fermentation to occur. Resulting mixture is called young beer.

Storage
The young beer is kept in a cool and pressurized tank.

Beer Filtering
The yeast and remaining proteins are filtered out to create “bright beer”. This product is controlled for alcohol and carbon dioxide content. The yeast is recycled and used again in approximately 20 more batches. Yeast is responsible for the particular taste of each type of beer brew, so companies prefer to reuse reliable yeast as much as possible before ordering a fresh strain.

Singha’s controlled alcohol content is 5% ABV, and the CO_2 is aimed to be 5.5 g/L beer. This information coupled with the basic fermentation reaction that is utilized in the beer brewing process,

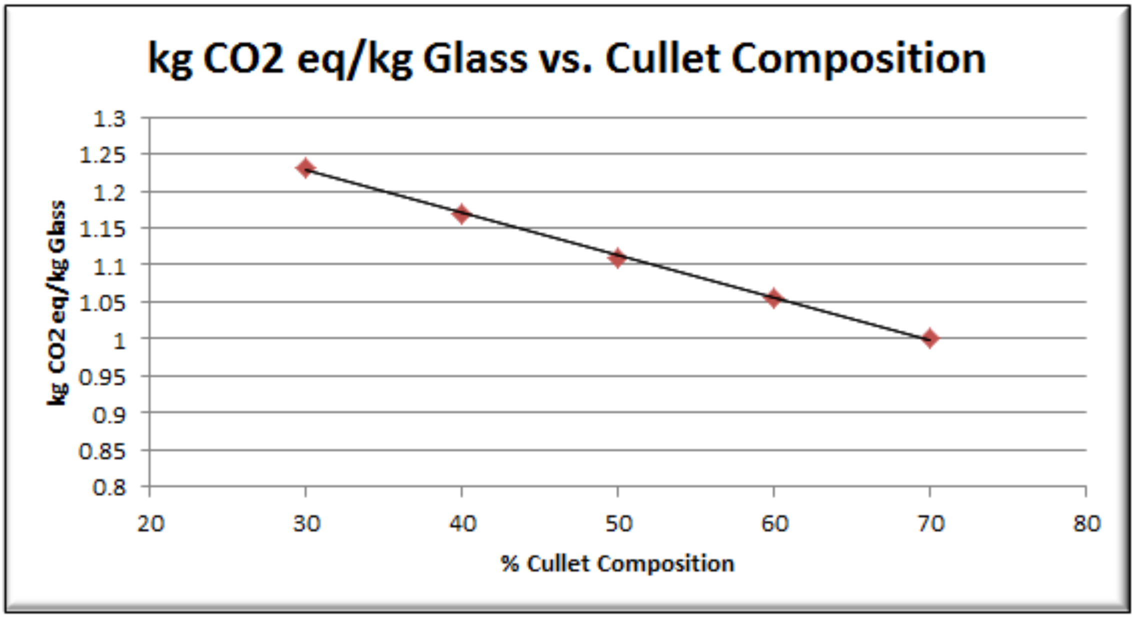
$$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2$$

allows for the preferred CO_2 content and resultant CO_2 amount produced via chemical reaction to be calculated. The calculations show 5,500 g CO_2 per functional unit of beer is desired within the Singha Lager, and the chemical reaction yields 19,062 L CO_2 resulting in 32 kg CO_2 (at standard temperature and pressure) being removed from the bright beer before bottling. This large amount of CO_2 can be dealt with in multiple ways. Some literature claims that biogenic CO_2 from the fermentation process of peer production can be recovered. The purified CO_2 can be used for purging beer bottles before filling to remove air and protect against oxidation. However, this is an expensive process, so it is assumed that within Pathum Thani Brewery the CO_2 would be released to the atmosphere, as this is more popular practice. A vacuum system is used to retrieve CO_2 from the atmosphere and purge the bottles rather than using the biogenic CO_2 mitigating the release of CO_2. Therefore, this large amount of CO_2 release is omitted from the brewery’s GWP impact.

2.5.2 Bottling

The Pathum Thani Brewery operates 24 hours a day, producing 20,000 bottles of Singha beer at 330 mL per hour. There are many studies available which display wide ranges of CO_2 eq emissions for glass bottle production. The variation is largely due to differences in the amount of cullet, or non-virgin glass, assumed and to the possibility of bottle reuse. According to the Bangkok Glass Company, which is the bottle provider for Singha, an increase in cullet composition of 10% results in a 5% carbon emissions reduction and 2-3% energy savings (Bangkok Glass Group, 2012). Beer bottles in Thailand are reused 5-10 times per year before being re-melted, although a study from Latin America (where refillables are over 60% of the market) reflects that these bottles could be used up to thirty times (Purdy et al, 2013). A Portuguese study also shows that the CO_2 emissions involved in cleaning reusable glass bottles are only 19% of the emissions produced from making a new bottle (Mata et al, 2001). The calculated carbon savings with regard to different cullet percentages are shown in Figure 3.

Figure 3



The inverse relationship between kg CO_2 eq per kg of glass versus percent cullet composition of beer bottle

The 330 mL glass bottle used for the final calculations in this study weighs 250 g and has 1.002 kg CO_2 eq emissions per kilogram associated with its production, including the impact 2of recycling at 70% cullet (an assumed number based on data from Thai Glass Industries (Raw, 2011). Adjusting to the functional unit at 3,030 bottles (756.6 kg glass), 759.1 kg CO_2 are emitted. Data for other impact categories was taken from an Indian study and is displayed below in Table 19. These values were then adjusted for fifteen times reuse.

Table 19: Impact category values of Singha glass bottles

Impact Category	Unit	Value per kg*	Value per FU (15x reuse)
GWP	kg CO_2 eq	1.002	50.61
Acidification	kg SO_2 eq	8.3E-03	0.42
Eutrophication	kg PO_4 eq	6.0E-04	0.03
Photochemical O_3	kg Ethylene eq	3.2E-04	0.016

*Values per kg of glass produced are taken from an Indian study (Life, 2012-Aigmf)

The glass bottles are recycled by partnering with Bangkok Glass Company. Regarding transportation of these bottles back to the recyclery to be remelted, a standard diesel lorry is assumed again and average fuel consumptions of an empty and full truck. The results show an additional 0.37 kg CO_2 eq being attributed to this remelting process when the glass bottles are returned to the glass company every 15 uses.

2.5.3 Aluminum Can Potential

An aluminum can of 355 mL has 131.5 g of CO_2 eq associated with its production, assuming 51.6% recycled content. When this is multiplied per functional unit, its impact is significantly less than a glass bottle, with 2,817 cans being produced and emitting 370.4 kg of CO_2 eq per 1000 L of beer. Further data was gathered from an LCA conducted by PE Americas, in which a closed-loop recycling approach was assumed. This data is displayed below in Table 20. (Life Aluminum, 2010).

Table 20: Impact category values for potential aluminum can

Impact Category	Unit	Value per Thousand Cans	Value per FU
GWP	kg CO_2 eq	131.5	370.4
Acidification	kg SO_2 eq	0.613	1.73
Eutrophication	kg PO_4 eq	1.565	4.41

The production emissions of a keg are lower than both of these bottling methods. Only 17 kegs are needed to hold 1000 L of beer and emit 21 kg of CO_2 during production. Kegs can be used indefinitely, allowing for frequent cleaning and maintenance. Each refilling and cleaning leads to 14 kg of CO_2 emissions per 1000 L of beer (Carbon Trust, 2011).

Packaging
Labels on the 330 mL glass bottles were found to not be significant contributors to CO_2 eq emissions, according to a 2012 study showing only 1.6 g CO_2 eq are emitted per label, translating to 4.85 kg CO_2 eq per FU (BIER, 2012).

The corrugated cardboard boxes used to house the cases of bottled beer are taken into account, as are the pallet impacts. For the 330 mL beer bottles, 24 bottles are packaged in each cardboard box and 40 boxes are on each pallet. Per functional unit, 126 cardboard boxes are needed, each with measured weights of 210 g. To determine the emissions associated with the production of these boxes, a study based on corrugated cardboard box production in Thailand was used. Table 21 displays the results. An average pallet lifetime is assumed at four uses (Lalonde, 2013). The impact categories are shown below in Table 22, as taken and altered from the "Life Cycle Assessment of Beer in Support of an Environmental Product Declaration" source (Lalonde, 2013). With this given pallet capacity and lifetime of a wooden pallet, the amount of pallets per functional unit is 3.19, which is used to allocate the impact category values below in Table 22.

Table 21: Corrugated cardboard box production Impacts (Ongmongkolkul et al, 2002)

Impact Category	Units	Per 0.655 kg box	Per 0.210 kg box	Per FU
GWP	kg CO_2 eq	0.75	0.24	30.2
Acidification	kg SO_2 eq	6.42E-03	2.06E-03	0.26
Eutrophication	kg PO_4 eq	2.37E-03	7.6E-04	0.096

Table 22: Wooden pallet impact information based on average values (Lalonde, 2013) of an average 4-use lifetime

Impact Category	Units	Average	per FU
climate change	Kg CO_2	0.62	0.49
acidification	G H^+	0.12	0.093
eutrophication	g N	1.33	1.05
water use	Liters	45	35.5
land use	m^2 yr	0.35	0.28

Water Treatment
Water is an important consideration for brewery operations, as approximately 70% of the water input is discharged. This is due to rinsing the vessels, hops and yeast cleaning, discharges from rinsing kegs and bottles before filling, and general beer spill clean-up processes (Brewers Association). Based on the necessary water input for the actual brewing process being 30% of the brewery's water use, the waste water volume was calculated to be 2079 L per functional unit, but no UASB waste water treatment mechanism is incorporated within Pathum Thani brewing branch of Singha Brewing.

Use
After beers have left the brewery in their respective packages, they are outside the scope of this study. It is still worth discussing the impacts of this step in the life cycle. Because the emissions of this stage are highly variable, the use phase did not seem practically quantifiable. The transportation distances from the brewery to retailers, distance traveled to purchase alcohol, and the refrigeration time periods before purchase and before consumption are some of the important but inconsistent energy intensive parts of the use phase. In the UK, 0.46% of all greenhouse gas emissions were from the refrigeration of beer, which is about 30% of the total emissions due to the brewing industry (Garnett, 2007). This is a substantial value and is worth considering in other studies.

3. Results

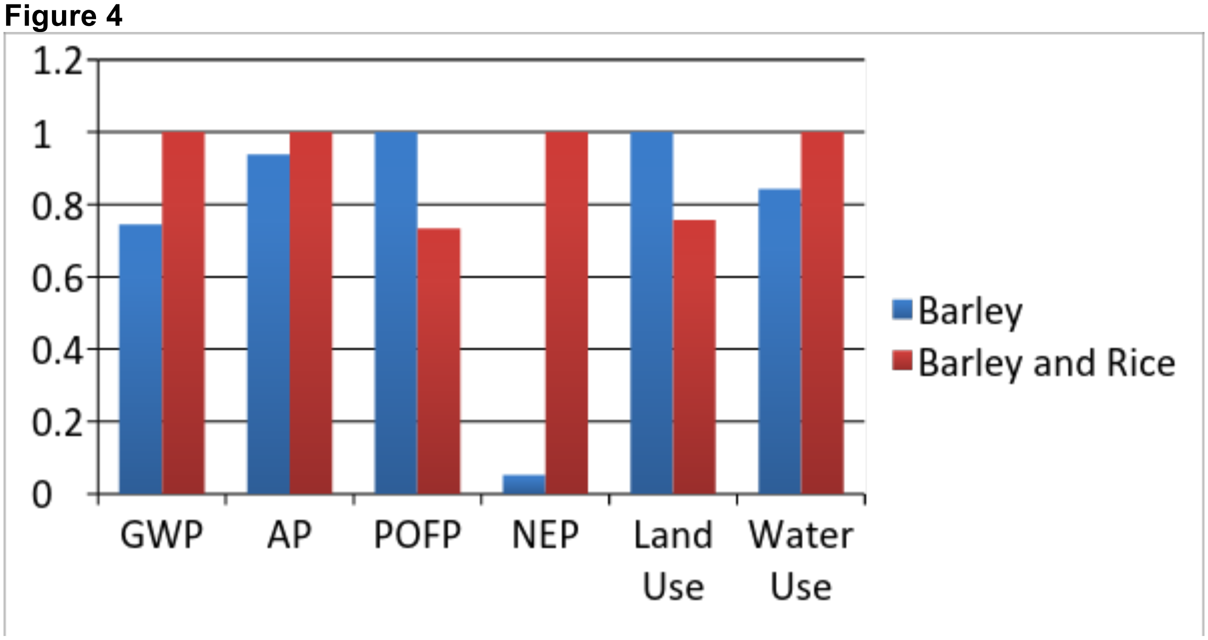
The following tables and figures represent the impacts of different steps of the brewing industry.

Table 23: Comparison of impact categories from the different cultivation methods

Impact Category	Unit	Barley	Barley and Rice
GWP	kg CO_2 eq	41.8	56.2
Acidification	kg SO_2 eq	0.079	0.085
Photo-Oxidant Formation	kg NMVOC eq	0.16	0.12
Nutrient Enrichment Potential	kg N eq	6.42E-03	0.12
Land Use	Hectares	0.063	0.048
Water Use	Liters	75600	89700

For a lager beer brewed with both barley and rice, the assumption that broken rice replaces 30% of the mass of the Singha 100% barley brew is made. Thus, 33.21 kg of rice are used per FU. The emissions from barley in the above table are calculated to be 70% of the 100% barley brew, and these impacts are added to the rice impacts.

Figure 4



Comparison of impact categories from the different cultivation methods

Figure 4 gives a visualization of the different impacts from the two different brewing inputs' cultivation demands.

Table 24: Impact values for total transportation

Impact Category	Unit	100% Barley, Hops, Yeast	70% Barley, 30% Rice, Hops, Yeast
GWP	kg CO_2 eq	4.60	5.33
Acidification	kg SO_2 eq	0.016	0.011
Photo-oxidant Formation	kg NMVOC	5.90E-7	6.9E-7
Nutrient Enrichment Potential	kg N eq	3.9E-6	4.6E-6

Table 25: Impact values from electricity use in brewery operations

Impact Category	Unit	Value per FU
GWP	kg CO_2 eq	9.14
Acidification	kg SO_2 eq	0.011
Photo-Oxidant Formation	kg NMVOC eq	0.013
Nutrient Enrichment Potential	kg N eq	0.0048
Water Use	Liters	2080

Table 26: Impact categories for the different containers of beer

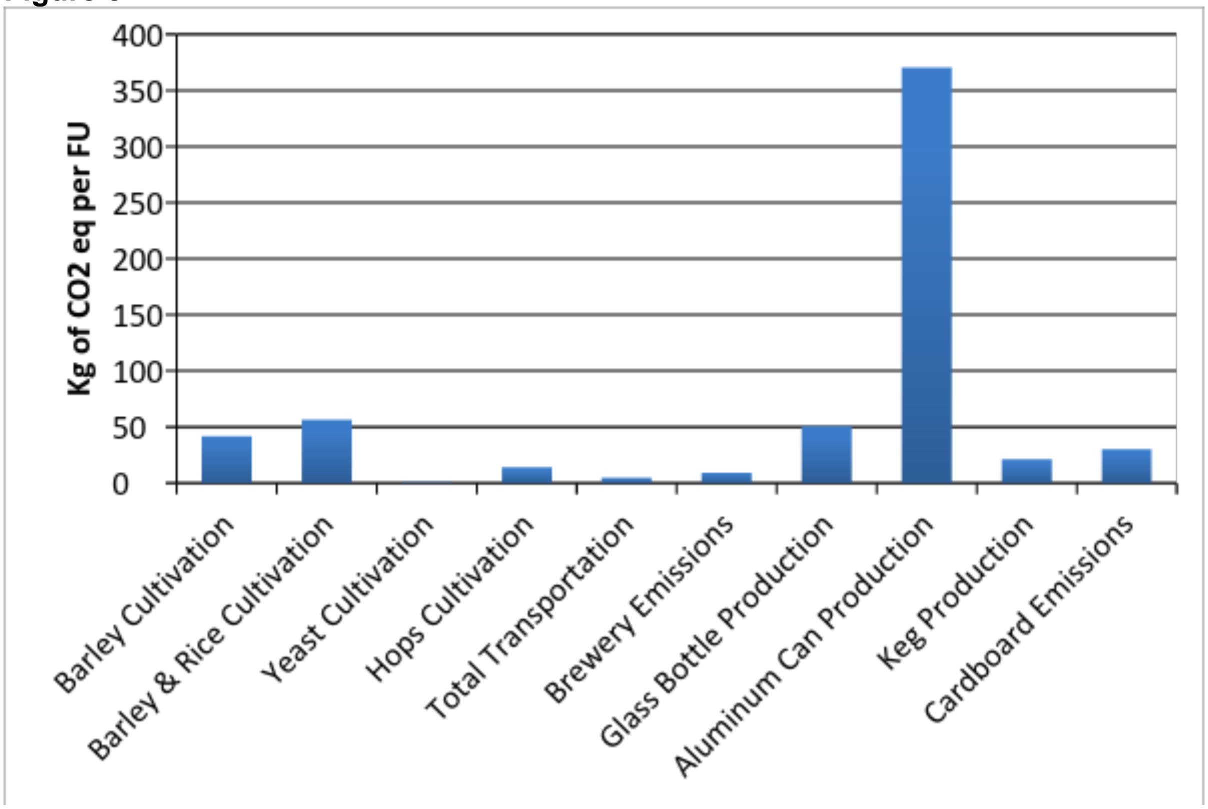
Impact Category	Unit	Glass Bottles	Aluminum Cans	Keg
GWP	kg CO_2 eq	50.9	370.4	21
Acidification	kg SO_2 eq	0.42	1.7	--
Eutrophication	kg PO_4 eq	0.0303	4.4	--

Table 27. GWP for all steps in the brewing process from cradle to gate in kg CO_2 eq

Process	GWP
Barley Cultivation	41.8
Barley & Rice Cultivation	56.2
Yeast Cultivation	0.8
Hops Cultivation	14.3
Total Transportation	5.1
Brewery Emissions	9.14
Glass Bottle Production	50.6
Aluminum Can Production	370.4
Keg Production	21
Cardboard Emissions	30.2

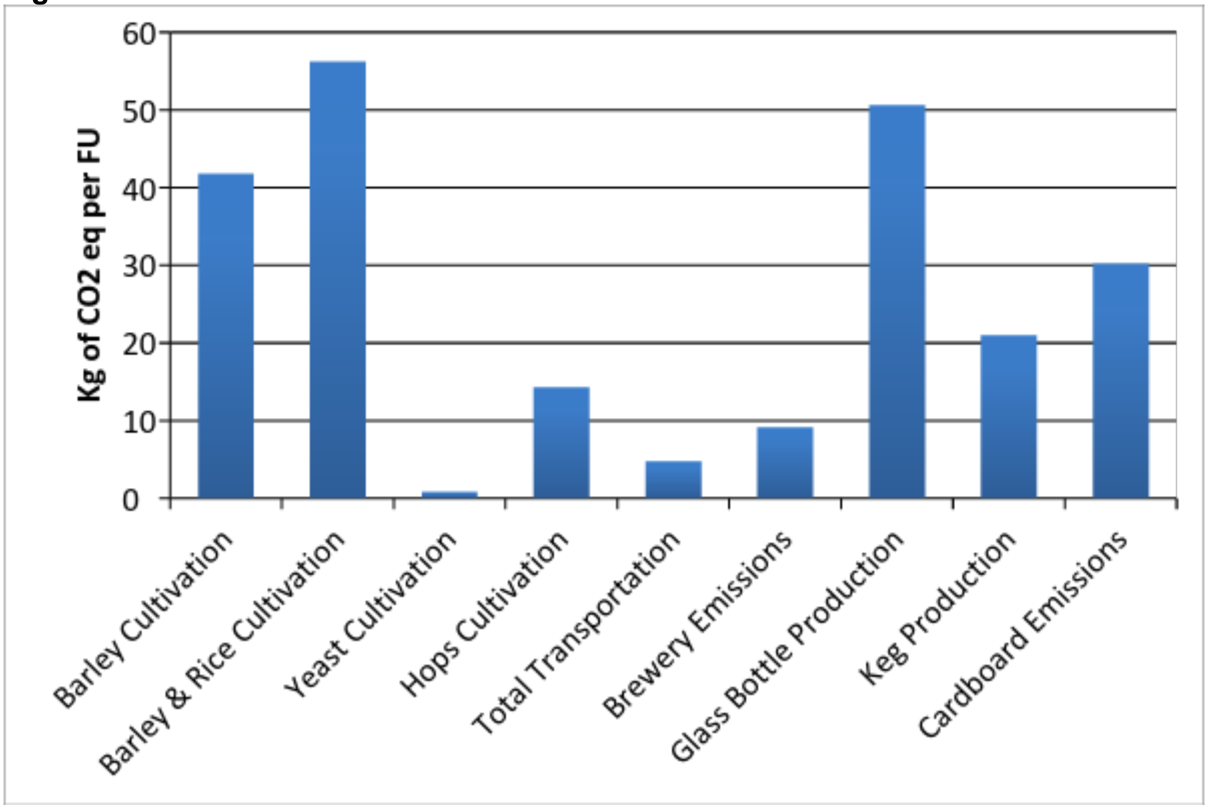
Table 27 is shown graphically in Figure 5 to make apparent the large and small impacts of the brewing process. Figure 6 shows the distribution barring the large aluminum can value to make impacts more visible.

Figure 5



GWP of the brewing industry

Figure 6



GWP distribution of the brewing industry excluding aluminum can production

Figure 6 excludes aluminum can production emissions to better see the impacts of the other steps.

Table 28: Total GWP of the different brewing recipes and packaging techniques

	Unit	Barley	Barley & Rice
Keg	kg of CO_2 eq	91.52	106.64
Glass Bottle	kg of CO_2 eq	151.37	166.49
Aluminum Can	kg of CO_2 eq	440.95	456.07

4. Discussion

4.1 Ingredients

A significant portion of the environmental effects of beer brewing are produced during the cultivation of ingredients. This study examined the process of brewing Singha, a 100% barley malt lager, but also considered how adding a 30% rice adjunct would alter emission outputs. After analyzing studies of Australian barley and Thai rice cultivation, it was determined that rice cultivation has higher environmental impacts in nearly every category. With regard to the carbon footprint, the 127.2 kg barley per FU used in a 100% barley beer was found to have 41.835 kg CO_2 eq emissions, while the 89.04 kg of barley and 33.21 kg rice used in brewing beer with a rice adjunct was found to have 56.22 kg CO_2 eq emissions, as seen in Table 23. This can be attributed to the large amounts of methane emissions produced during rice cultivation due to methanogenesis in the waterlogged soil. This makes for a high impact as methane has 25 times the GWP of CO_2. The rice adjunct also contributes to a larger nutrient enrichment potential and significantly increases water use, with an additional 14,100 L being used per FU. Land use decreases by 0.0153 Ha per FU when rice is used, presumably from higher crop yields per hectare. Figure 4 shows the variations in all of the impact categories. The local impacts of pesticide runoff were excluded from this study as the data did not include this potential.

While data regarding the emissions of hops cultivation was limited, the 14.3 kg CO_2 eq emissions released per FU are significant, as only 1.45 kg of hops are needed per 1,000 L of beer. This suggests that hops cultivation is a heavy contributor to the environmental burdens of beer production, and further study should be done to help quantify and mitigate these effects. Yeast production only contributes 0.842 kg CO_2 eq emissions per FU, a relatively insignificant amount compared to other processes. However, much of the insignificance of this number is a result of the reuse of yeast by the brewing industry. Large breweries such as Pathum Thani typically reuse yeast up to twenty times before it is discarded, a method that produces both economic and environmental savings.

4.2 Brewing Process

Much of the equipment used in the Pathum Thani Brewery is powered by electricity. The brewery reported an electricity consumption rate of 1320 kWh per batch, or 15 kWh per FU. This value was used to determine the emissions produced from the Thai grid, and 9.14 kg CO_2 eq emissions were found to be released. The emissions from the Thai grid produce the third smallest carbon footprint out of the processes analyzed in this study. Table 25 shows the impacts studied were relatively small as well, with 0.00476 kg N eq and 0.01083 kg SO_2 eq being released per FU. This shows a lower nutrient enrichment potential and acidification potential than either cultivation method. Water use in the brewery was determined to be 2,079 L per FU. While this value appears low when compared with water use during grain production, efficient water use within breweries remains an issue that plagues the industry. On average, 70% of water that enters the brewery is discharged as effluent with a high percentage of organic compounds absorbed during routine washing of equipment. This wastewater is a local impact that was not taken into account for environmental impacts.

4.3 Packaging

A large contributor to the impacts assessed in this study is the use of packaging materials. Two main containers were included in the scope: a 355 mL aluminum can and a 330 mL glass bottle. Glass bottles were adjusted for fifteen times reuse and were assumed to have a 70% cullet composition, significantly reducing their impacts. Even after adjustment, glass bottles were the third highest contributors to GWP, after aluminum can production and cultivation of barley with a rice adjunct. Glass production also had the second highest acidification potential at 0.42 kg SO_2 eq emissions. These values can be seen and compared in Table 26.

Aluminum can production had over seven times the GWP of glass bottle production and was the largest contributor to acidification as well as having a significant contribution to nutrient enrichment potential at 4.41 kg PO_4 eq. The 355 mL cans used for this study were assumed to have a recycled content of 68%, but the impacts produced by bauxite mining and electrolysis in the aluminum production process for virgin aluminum are still very substantial. The smallest carbon footprint for container options was a keg, with only 21 kg CO_2 eq emissions produced per FU.

The corrugated cardboard boxes used to package glass bottles contribute 30.24 kg CO_2 eq per FU, which is the fourth highest GWP among studied categories. Cardboard production also has the third highest acidification potential after aluminum and glass production. Wooden pallets are used to transport the boxes. Their assumed lifetime of four uses reduces their GWP to 0.485 kg CO_2 eq per FU, a relatively low impact.

4.4 Transportation

Transportation did not contribute significantly to any impact categories when compared with the cultivation of grains or production of aluminum and glass, as seen in Table 24. The emissions are mainly from the combustion of diesel by trucks and ships. After totaling the emissions from transportation of ingredients and for two different recipes, it was found that total transportation contributes either 4.23 kg CO_2 eq or 4.96 kg CO_2 eq emissions -- the second smallest GWP among analyzed processes. Approximately 0.0159 kg SO_2 eq or 0.0112 kg SO_2 eq are emitted per FU, producing a relatively low acidification potential. It is worth noting that the environmental impacts of shipping 30% less barley from Australia to Thailand and substituting it with Thai broken rice that was driven 480 km by land had a larger impact. This shows the immense impacts that land transportation has on the environment. For GWP the impact only increased by about 0.73 kg of CO_2 eq, but that is still 17% higher than when only barley was shipped. Thus, importation of all barley is less costly to the environment than incorporating native rice production into the brew.

5. Conclusion

Thailand consumes 1,890,000,000 L of beer per year (Kirin Holdings, 2014). The functional unit of this study is 1000 L of beer. This means that the impacts from this study could be multiplied by 1,890,000 to get the impact of one year of beer production relative to the country's consumption. In CO_2 equivalence that would be about 286 kilotonnes of CO_2 eq emissions, which is approximately 0.1% of Thailand's CO_2 emissions annually (The World Bank, 2014). This calculation doesn't take into account imports and exports, but is a way to represent the impact of the industry, which is the same order of magnitude as all of the annual CO_2 emissions from countries like Greenland (634 kt) or Rwanda (594 kt) (The World Bank, 2014).

This paper concludes from Table 28 that the environmental impact of beer brewing is minimized using a 100% barley brew and packaging it in a keg. From the options analyzed, 70% barley and 30% malt that is packaged in aluminum cans has the largest impact and should consciously be avoided to minimize the environmental impacts of the brew and packaging.

The attached infographic puts the global warming potential of inputs, transportation, and packaging in perspective of other more common activities to all citizens. For example, the emissions from barley are approximately the same as the USA per capita carbon footprint per day, and the barley and rice cultivation mixture exceeds this value by about 8 kg CO_2. Hops cultivation is approximately equivalent to Thailand's per capita carbon footprint per day of 12 kg CO_2. Transportation emissions are comparable to Thailand's average commuting per day CO_2 emission, at 4.4 and 3.4 kg CO_2 eq respectively. Also, while natural breathing emits approximately 1.04 kg CO_2 per day, glass bottle production and aluminum can production per functional unit emit 0.4 and 3.2 kg CO_2, respectively.

5.1 Limitations of the Study

The lack of detailed data on hops cultivation represents a major limitation to this study, and this data could be further analyzed in the future. Since a basic assumption is currently in use, a more accurate value of hops production in Germany is necessary for improvement. While reputable secondary data was used for determining the emissions of many processes examined in the study, an increase in primary data would provide a more accurate basis for comparing outputs.

5.2 Recommendations

The Boon Rawd Singha Brewing facility uses a UASB+AS wastewater treatment process to treat the wastewater produced from beer, but the correspondents at Pathum Thani brewery stated that no biogas is created at their facility, and it was assumed that no UASB system is present. Fully understanding the wastewater treatment system that is in use at Pathum Thani would be important and a comparison between the two systems would be beneficial.

To make the yeast impacts more accurate, a precise amount of the CO_2 needed to purge the beer bottles before filling would be necessary. There is a significant amount of CO_2 that is naturally released from the fermentation process because a large amount is produced that is not needed in the beer for carbonation (see section 2.5). Presumably, this is released to the atmosphere. Also, to purge the empty beer bottles and prevent against oxidation, CO_2 can be used. This CO_2 is usually taken from the atmosphere. Recycling biogenic CO_2 from fermentation into the purging process is expensive and not as common. Thus, if it is assumed purging CO_2 is taken from the air and fermented CO_2 is released to the air, it is potentially a carbon neutral process. This is the assumption being made, but is not necessarily accurate because it is unclear how much CO_2 is needed in bottle purging. This is thus a point of recommendation within this paper that would make the GWP calculations more accurate.

Aluminum can emissions are an issue in this paper. Although numerous sources confirm the values stated in this study, it is substantially higher than every other category. The resource from which the aluminum cans data came includes the impact of mining the bauxite ore and all associated emissions, an extremely energy intensive process which can be mitigated by increasing the recycled content of beverage cans. Studies show that aluminum recycling is incredibly effective, with 95% energy savings when compared to extraction of virgin materials. Glass recycling is less beneficial from an energy standpoint, with 30% savings produced with non-virgin material use. However, the numbers used to represent Thailand's recycled aluminum and glass content in this study still show that glass bottles are the preferred packaging choice environmentally, but only when reused a minimum of seven times (Stanford University, 2000). To improve this issue, all of the resources used within this process could be taken to extraction emissions.

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