Sustainability Assessment of U.S. Beef Processing and its Antimicrobial Systems

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SUSTAINABILITY ASSESSMENT OF U.S. BEEF PROCESSING AND ITS ANTIMICROBIAL SYSTEMS

by

Shaobin Li

A DISSERTATION

Presented to the Faculty of The Graduate College at the University of Nebraska

In Partial Fulfillment of the Requirements

For the Degree of Doctor of Philosophy

Major: Civil Engineering
(Environmental Engineering)

Under the Supervision of Professors Bruce Dvorak and Jeyamkondan Subbiah

Lincoln, Nebraska

July, 2019
SUSTAINABILITY ASSESSMENT OF U.S. BEEF PROCESSING AND ITS ANTIMICROBIAL SYSTEMS

Shaobin Li, Ph.D.
University of Nebraska, 2019

Advisors: Bruce Dvorak and Jeyamkondan Subbiah

With the increasing meat demand and awareness of sustainability, concerns have been raised regarding the sustainability of beef production and processing. However, scarce data and inadequate sustainability assessment frameworks for the U.S. beef processing industry limit the ability to develop new technologies and policies comprehensively without shifting sustainability burdens. To fill those gaps, various assessments of the U.S. beef processing industry were conducted from multiple perspectives regarding the environmental, economic, microbial effectiveness of its antimicrobial systems, and human health impacts from foodborne illness, occupational hazards, and environmental pollution.

First, process-level water and energy usage at a typical large-size beef processing plant were benchmarked and compared to available data in the literature, and then opportunities were identified for water and energy reduction. The collected inventory data were subsequently utilized as inputs to assessment models. Second, the environmental and economic sustainability of three antimicrobial systems deployed in commercial beef processing industry were evaluated. The results show that chemicals, natural gas, and wastewater dominate all environmental impact indicators and antimicrobial systems with thermal pasteurization resulting in meat discoloring that can reduce revenue. Third, the study scope of sustainability assessment of antimicrobial
systems was broadened. Specifically, 40 possible combinations of antimicrobial systems were analyzed, and the analysis incorporated the microbial effectiveness via meta-regression with the environmental and economic assessment. The evaluation identified that the use of steam results in the best combination of low cost and environmental impact, and high microbial reduction.

Fourth, the trade-offs between foodborne illness, environmental impacts, and occupational hazards on human health from the U.S. beef slaughtering and consumption were investigated. The results show that the three impacts on are the same magnitude and 42% of environmental impacts on human health is from processes directly related to microbial food safety. Potentially reductions in foodborne pathogens achieved by resource-intensive food safety interventions should be considered jointly with environmental impacts and occupational hazards to prevent unintended shifts or increases in human health impact. Last, environmental impacts of beef processing via an integrated hybrid LCA were quantified to incorporate environmental impacts embedded with background economic activities, such as technical and financial services.
This dissertation is dedicated to my parents

Mr. Jianchang Li and Mrs. Fengting Wang;

and to my many family members

For their endless love and unconditional support
ACKNOWLEDGEMENT

First, I would like to express my deepest appreciation to my two dear advisors Dr. Bruce Dvorak and Dr. Jeyamkondan Subbiah for all of their support and guidance. I am grateful to them for giving me as a young teenager an opportunity five years ago to work in their groups on many interesting projects. I appreciate many conversations and guidance from them which have helped me grow professionally and enrich my skills through the development of this work. Both of them are mentors to me by showing me examples of how to work hard and think critically. I sincerely thank Dr. Dvorak for encouraging and guiding me to brainstorm innovative research ideas and involving me in proposal preparations, which helped prepare me as an independent researcher in the future. I also truly appreciate Dr. Subbiah for always being open-minded and being supportive of research ideas I proposed, which has inspired me to dream big and stay passionate about research.

I would like to thank my doctoral committee members, Dr. Xu Li, Dr. Yusong Li, and Dr. Yulie Meneses for committing their time to support my research. I wanted to especially thank Dr. Xu Li who is not only my doctoral committee member but also my gym partner. As we routinely work out together twice to three times a week, I have the opportunities to draw wisdom from Dr. Xu Li by chatting with him on many topics regarding academic and personal life.

I appreciate the people at commercial beef processing plants in Nebraska for helping me tackle many real-world challenges in industrial practices. I would like to thank the undergraduate interns, Courtney Kinser and Samuel Hansen, for helping collect
the data on beef processing plants. I also appreciate my colleagues at UNL, including Dr. Rami Ziara, Dr. Jian Li, Matthew Thompson, and Sussan Moussavi for involving me in multiple interesting projects. I am grateful to the faculty and staff at the Department of Civil Engineering at UNL under many circumstances. I sincerely thank all the friends I met at UNL for all the great memories.

Over the past five years, I have been lucky to know more about the great traditions of the Husker football program and have become a loyal fan. I have been motivated by husker spirits and considered myself as an academic husker. I have found there are many shared spirits between the athletic huskers and academic huskers. They are integrity, diligence, dedication, mental toughness, and team spirit.

Finally, I am forever indebted to my parents for instructing me to live the life I love today. This work would have never been possible without the endless love and unconditional support from them. My gratitude to them is beyond what words can express.

Thank you all again for being a part of my journey at UNL. Once a Husker, always a Husker! GO BIG RED!
PREFACE

The results from Chapter 2 have been published in *Journal of Food Process Engineering*:

**Li, Shaobin**, Rami MM Ziara, Bruce Dvorak, and Jeyamkondan Subbiah.


The results from Chapter 3 have been published in *Journal of Cleaner Production*:


The results from Chapter 4 have been published in *Science of The Total Environment*:


The results from Chapter 5 have been published in *Environmental International*:

**Li, Shaobin**, Jeyamkondan Subbiah and Bruce Dvorak. “Environmental and occupational impacts from U.S. beef slaughtering are of same magnitude of beef

The results from Chapter 6 are currently in preparation for submission:

**Li, Shaobin, Yuwei Qin, Jeyamkondan Subbiah and Bruce Dvorak.** “Life cycle assessment of U.S. beef processing through process-based and integrated hybrid approaches,” in preparation.

My contribution was to design and perform each research project from Chapter 2 to Chapter 6, including developing the methodology, collecting and analyzing data. I also served as the lead author in writing each manuscript. Dr. Bruce Dvorak and Dr. Jeyamkondan Subbiah provided guidance on refining the research and gave comments on all manuscripts. Dr. Rami MM Ziara helped on some data collection in industrial plants for Chapter 2. Courtney Kinser and Dr. Rami MM Ziara helped on some data collection for Chapter 3. Samson Zhilyaev and Dr. Daniel Gallagher from Virginia Polytechnic Institute and State University helped conducted the meta-analysis of different combinations of antimicrobial systems for Chapter 4. Dr. Yuwei Qin from University of California, Santa Barbara helped conduct uncertainty analysis for Chapter 6.
Table of Contents

List of Figures .......................................................................................................................... xiii
List of Tables ............................................................................................................................. xvi

1. Introduction ............................................................................................................................. 1
   1.1 Overview of U.S. beef processing industry and its processing steps ......................... 1
   1.2 Introduction to life cycle assessment ........................................................................... 4
   1.3 Past sustainability analyses of beef processing ......................................................... 5
   1.4 Research motivation and objectives .......................................................................... 8
   1.5 Organization of the dissertation ................................................................................ 10

2. Assessment of water and energy use at process level in the U.S. beef processing industry: case study in a typical U.S. large-size plant ........................................ 12
   2.1 Abstract ....................................................................................................................... 12
   2.2 Introduction ............................................................................................................... 13
   2.3 Methodology .............................................................................................................. 15
      2.3.1 Process-level data collection ............................................................................. 16
      2.3.2 Evaluate impacts of operating capacity and outdoor temperature on water and energy use at processes level ........................................ 19
   2.4 Results and discussion .............................................................................................. 20
      2.4.1 Water usage at process level ............................................................................. 20
      2.4.2 Energy usage at the process level ..................................................................... 25
      2.4.3 Comparison of water and energy use with previous studies ............................. 27
      2.4.4 Multiple linear regression analysis of water and energy use at various processes ......................................................................................... 29
      2.4.5 Summary of water and energy efficiency measures ....................................... 32
   2.5 Conclusions ................................................................................................................ 33

3. Compare environmental and economic impacts of three antimicrobial systems commercially applied in U.S. beef processing industry ...................... 35
   3.1 Abstract ....................................................................................................................... 35
   3.2 Introduction ................................................................................................................ 36
3.3 Methodology..............................................................................................................................................39  
3.3.1 Description of the three scenarios of sequential antimicrobial systems .............................................39  
3.3.2 Goal and scope ........................................................................................................................................41  
3.3.3 Life cycle inventory (LCI) ....................................................................................................................42  
3.3.4 Life cycle impact assessment ...............................................................................................................46  
3.3.5 Monte Carlo simulation and Pedigree matrix approach for uncertainty analysis ............................47  
3.3.6 Operating cost analysis .........................................................................................................................48  
3.4 Results and discussion ..............................................................................................................................50  
3.4.1 Normalized environmental impacts comparison ..................................................................................50  
3.4.2 Components contribution ....................................................................................................................53  
3.4.3 Intervention steps contribution ............................................................................................................56  
3.4.4 Comparison of relative operating costs ...............................................................................................58  
3.4.5 Limitations and future work ...............................................................................................................60  
3.5 Conclusions ..................................................................................................................................................61  
3.6 Appendix: Supporting information ........................................................................................................63  
3.6.1 List of background database, modeling wastewater treatment plant, manufacturing peracetic acid (PAA) solutions ........................................................................................................63  
3.6.2 Inventory of cabinets, water, energy, and chemicals use for production of 1000 kg HSCW ..........64  
3.6.3 Thermal energy and electricity use for production of 1000 kg HSCW ..............................................67  
3.6.4 Wastewater BODs loadings and modeling of wastewater treatment plant ..................................68  
3.6.5 Inventory of peracetic acids (PAA) solutions manufacturing route ..............................................70  

4. Integrating environmental and economic assessment with food safety effectiveness for antimicrobial systems in U.S. beef processing .................................................................73  
4.1 Abstract .........................................................................................................................................................73  
4.2 Introduction ..................................................................................................................................................74  
4.3 Methodology ..............................................................................................................................................76  
4.3.1 Configurations of the 40 proposed antimicrobial systems .............................................................76
4.3.2 Meta-analysis on microbial load reduction for various antimicrobial interventions ................................................................. 78
4.3.3 Environmental and economic analyses ........................................ 80
4.3.4 Assumptions and uncertainty analyses ...................................... 82
4.4 Results and discussion ................................................................... 84
4.4.1 Sequential microbial load reduction ........................................... 84
4.4.2 Environmental impact assessment ............................................. 87
4.4.3 Economic analysis .................................................................... 89
4.4.4 Interactions among environmental impacts, costs, and food safety ....... 91
4.5 Conclusions .................................................................................. 95
4.6 Appendix: Supporting information ................................................ 98
4.6.1 Description of antimicrobial interventions investigated in this study ...... 98
4.6.2 Meta-regression equations applied in this study ............................ 99
4.6.3 Inventory data ........................................................................ 100

5. Comparing foodborne, environmental and occupational human health
   impacts from the U.S. beef slaughtering and consumption ................... 109
5.1 Abstract ...................................................................................... 109
5.2 Introduction ................................................................................ 110
5.3 Methodology ................................................................................ 113
5.3.1 Disease burden of foodborne illnesses from beef consumption ....... 115
5.3.2 Disease burden of environmental risks from beef slaughtering .......... 116
5.3.3 Disease burden of occupational risks from beef slaughtering .......... 120
5.3.4 Normalization reference ........................................................... 121
5.3.5 Uncertainty estimates .............................................................. 122
5.4 Results and discussion ................................................................ 123
List of Figures

Figure 1.1 Process flow of a typical large-size beef processing facility in the U.S. ............ 3

Figure 1.2 Objectives map for sustainability assessment of U.S. beef processing in this dissertation ........................................... 11

Figure 2.1 Layout of processes with water meter system in the studied beef processing facility ........................................... 17

Figure 2.2 Average daily water use pattern. Data averaged from one week from two pipes: a) overall water inlet; b) water usage with a temperature of 43°C ................. 21

Figure 2.3 Process-Level electrical use (overall electricity use= 106.7 ± 13.8 kWh/t LCW) ........................................... 26

Figure 3.1 Process routes of three antimicrobial systems, detailing the operational parameters in each intervention. Note: PAA represents peracetic acid. ................. 40

Figure 3.2 Relevant components and energy flows considered in the antimicrobial systems boundary of the LCA model......................... 43

Figure 3.3 The normalized environmental impacts across three antimicrobial systems. . 52

Figure 3.4 Relative life cycle impact contributions of antimicrobial systems by components ........................................... 54

Figure 3.5 Relative life cycle impact contributions of antimicrobial systems by intervention steps ........................................... 57

Figure 3.6 Comparative operating cost analysis of three scenarios of antimicrobial systems ........................................... 59

Figure 4.1 Configurations of antimicrobial systems ........................................... 78
Figure 4.2 System boundary and scope of the integrated assessment of antimicrobial systems in the study ........................................................................................................ 81
Figure 4.3 Sequential microbial load reduction from the three steps, (a) Pre-evisceration wash (Prewash), (b) Carcass wash, and (c) Main intervention ........................................ 86
Figure 4.4 Environmental single scores of different interventions ........................................ 88
Figure 4.5 Cost of different interventions. (2-column) .......................................................... 90
Figure 4.6 Bubble plot of interactions among environmental impacts, operational costs, and microbial log reductions for the 40 systems studied ........................................ 92
Figure 5.1 Schematic view of the framework for determining disability-adjusted life year (DALY). Note: BLS = Bureau of Labor Statistics. .................................................. 114
Figure 5.2 System boundary of the U.S. beef slaughtering in this study ................................. 117
Figure 5.3 Ranking of disability-adjusted life year (DALY) caused from seven primary pathogens normalized by beef weight (y-axis) and by the number of cases (x-axis). .................................................................................................................................... 123
Figure 5.4 Disability-adjusted life year (DALY) by various environmental midpoint categories from beef slaughtering: (A) Breakdown of environmental impacts using ReCiPe method. (B) Comparison of human toxicity result from two methods (i.e., ReCiPe 2016 and USEtox 2.0) ......................................................................................................................... 125
Figure 5.5 Disability-adjusted life year (DALY) caused by various occupational hazards during beef slaughtering. ........................................................................................................ 127
Figure 5.6 Comparison of the three impacts on human health .............................................. 130
Figure 6.1 System boundary and methodology framework .................................................. 168
Figure 6.2 Structure of integrated hybrid LCA model for beef processing ............................ 170
Figure 6.3 Impact assessment method, normalization, and weighting in this study...... 172

Figure 6.4 Contributions of specific processes to environmental life cycle impacts of the US beef processing ........................................................................................................ 176

Figure 6.5 Integrated hybrid LCA midpoint results of the US beef processing .......... 178

Figure 6.6 Integrated hybrid LCA environmental single score of the US beef processing ................................................................................................................................. 179

Figure 6.7 Violin plot of environmental categories representing the sampling distribution from Monte Carlo simulation (10,000 runs). ......................................................... 180

Figure 6.8 Contribution to output variance for Sobol’s total sensitivity index of the selected inventory parameters (i.e., usage and prices). ................................................. 182

Figure S4.1 Univariate k-means clustering of overall log reductions for the 40 antimicrobial systems studied................................................................. 105

Figure S4.2 Pairwise comparison of 40 antimicrobial systems under Monte Carlo (MC) simulation (1,000 runs). ................................................................. 106

Figure S4.3 Bubble plot of interactions among environmental impacts, operational costs (assuming no devalued meat occurred), and microbial log reductions for the 40 systems studied. ................................................................. 107

Figure S4.4 Correlation plot of two weighting schemes applied to 40 antimicrobial systems under two assumptions of devalued meat. Note: HSCW= hot standard carcass weight. .................................................................................. 108
**List of Tables**

Table 2.1 Process-level water use ................................................................. 23
Table 2.2 Process-level thermal energy use ..................................................... 27
Table 2.3 Multiple linear regression analysis of water and energy use at various processes. Impacts on total water or energy savings are highlighted in bold. .......... 31
Table 6.1 Environmental impacts of U.S. beef processing for 1000 kg LCW .......... 177
Table S3.1 List of the background dataset used ................................................. 63
Table S3.2 List of the dataset used for modeling wastewater treatment plant .......... 64
Table S3.3 List of the dataset used for manufacturing peracetic acid (PAA) solutions .... 64
Table S3.4 Estimated weight, service life, and materials of cabinets assembly .......... 65
Table S3.5 Inventory of water, energy, and chemicals use for 1000 kg HSCW .......... 66
Table S3.6 Breakdown of thermal energy use for production of 1000 kg HSCW .......... 67
Table S3.7 Breakdown of electrical energy use for production of 1000 kg HSCW ....... 68
Table S3.8 Wastewater BOD₅ loadings from each antimicrobial intervention for production of 1000 kg HSCW ................................................................. 69
Table S3.9 Resources input and emissions associated with a typical industrial anaerobic wastewater treatment plant for treating 1 m³ wastewater ........................................ 70
Table S3.10 Inventory of peracetic acids (PAA) solutions manufacturing route .......... 71
Table S3.11 Detailed environmental impact results by components ....................... 72
Table S4.1 Description of antimicrobial interventions investigated in this study ........ 98
Table S4.2 Meta-regression equations applied in this study .................................. 99
Table S4.3 List of all 40 designs of antimicrobial systems investigated in this study ... 100
Table S4.4 Foreground inventory data used in this study .................................... 101
Table S4.5 Selected background processes from U.S.-EI 2.2 and Ecoinvent 3 databases (LTS, 2016; Wernet et al., 2016) ................................................................. 102

Table S4.6 Environmental impacts of 1 kg hot standard carcass weight (1 kg HSCW) on the farm stage ........................................................................................................................................ 103

Table S4.7 Normalization value calculated and weighting coefficients of TRACI environmental impacts (Meijer, 2013; Ryberg et al., 2014) ...................................................... 104

Table S4.8 Breakdown of cost in each intervention treatment ........................................ 104

Table S5.1 Foodborne illnesses attributed to beef by 9 major pathogens .................... 136

Table S5.2 Disease burden (DALY) per 1000 foodborne illnesses related to the seven primary pathogens from two published studies .................................................. 137

Table S5.3 Disease burden (DALY) of foodborne illnesses attributed to 1000 kg live cattle weight by major pathogens. ............................................................... 138

Table S5.4 Data collection of onsite resources consumed and solid waste input........... 140

Table S5.5 Life cycle inventory background processes and databases chosen for evaluating environmental impacts of beef slaughtering ........................................... 141

Table S5.6 Inventory background processes and databases chosen for evaluating environmental impacts of rendering ................................................................. 142

Table S5.7 Inventory background processes and databases chosen for evaluating environmental impacts of manure disposal and management ............................ 142

Table S5.8 Process contribution analysis of total environmental impacts on human health (DALY/1000 kg LW beef) ................................................................. 143

Table S5.9 Substance contribution analysis of human toxicity on human health from ReCiPe 2016 method (Huijbregts et al., 2017) ......................................................... 144
Table S5.10 Substance contribution analysis of human toxicity on human health from USEtox method (Marian Bijster et al., 2017) ................................................................. 144

Table S5.11 Difference contribution by substance of human toxicity on human health between USEtox 2.0 and ReCiPe 2016 methods. ...................................................... 145

Table S5.12 Number of nonfatal injuries and illnesses of three involved NAICS codes 148

Table S5.13 Total cases of nonfatal injuries and illnesses by BLS age strata(Bureau of Labor Statistics and Injuries, Illnesses, 2015b) ................................................................. 149

Table S5.14 Conversion of total cases of nonfatal injuries and illnesses by BLS age strata to WHO age strata ...................................................................................................... 149

Table S5.15 WHO age strata weighted multipliers for nonfatal injuries and illnesses .. 150

Table S5.16 Partitioning coefficient of life-long and short-term nonfatal injuries or illnesses ......................................................................................................................... 150

Table S5.17 Details regarding the partition of life-long and short-term injuries using BLS nature codes .............................................................................................................. 151

Table S5.18 Total cases of short-term nonfatal injuries per injury per age strata ........ 152

Table S5.19 Total cases of life-long nonfatal injuries per injury per age strata .......... 153

Table S5.20 Duration of short-term injuries and illnesses (Dc, a, ST) obtained from BLS (Bureau of Labor Statistics and Injuries, Illnesses, 2015c) ............................................. 154

Table S5.21 Duration of life-long injuries and illnesses (Dc, a, LL) between male and female .......................................................................................................................... 154

Table S5.22 Disability weights of short-term and life-long nonfatal injuries .......... 155

Table S5.23 Details regarding matching BLS nature codes with WHO health states and selecting disability weight .......................................................................................... 156
Table S5.24 Results of short-term and life-long YLD...................................................... 157
Table S5.25 Results of YLL of interested NAICS codes ........................................... 158
Table S5.26 Livestock and poultry data from USDA ERS (USDA ERS, 2016) and their corresponding NAICS codes................................................................. 159
Table S5.27 Projected janitorial workers demographics for beef slaughtering industry 159
Table S5.28 Results for NAICS 56172 and 5617 ......................................................... 160
Table S5.29 Summary of DALY from occupational risks connected to the U.S. beef slaughtering industry................................................................. 160
Chapter 1

1. Introduction

1.1 Overview of U.S. beef processing industry and its processing steps

The production of meat in the world is expected to increase twofold by 2050 to meet the demand of increased world population and increase prosperity in 2050 (Steinfeld et al., 2006). With its abundant grain production and vast rangeland available for cattle, the U.S. beef industry is the world’s largest producer of beef with around 19.7% of the 2018 global beef production (USDA FAS, 2019). As of 2015, the U.S. beef processing industry slaughtered 28.7 million head of cattle with $105 billion of estimated retail equivalent value (USDA ERS, 2016). As the beef processing industry is a significant component of U.S. food industry, it also requires intensive consumption of resources (e.g., water, energy, packaging materials, chemicals) and releases environmental pollutants (e.g., wastewater, solid waste, greenhouse gases, air pollution) (Battagliese et al., 2015; Djekic and Tomasevic, 2016; Peters et al., 2010). Studies have shown that the farm stage contributes most life-cycle environmental burdens of the whole beef supply chain. However, it is still essential to evaluate the current sustainability of beef processing sector because: 1) beef processing sector consumes intensive resources and produces high strength wastes; 2) beef processing sector in the U.S. is highly
centralized with four big corporations producing 80% of the beef (National Cattleman’s Beef Association, 2016), while 97% of 2.1 million farms are primarily family-owned farms widely dispersed in the U.S (USDA NASS, 2015). Thus sustainability improvements may be easier to implement at beef processing stage than at the farm stage.

A general process flow in a typical U.S. beef processing facility is provided in Figure 1.1. Cattle are delivered to the holding yard where cattle rest for about 24 hours to release stress and are washed to remove dirt and manure on hide. The cattle are then driven to the slaughtering area where they are stunned and are shackled from an overhead rail by hind legs. The cattle are then bled, and blood is collected in cans for further processing. Next, the cattle undergo limb trimming, hide and head removal. The hides are sent off for washing and processing, and the heads are removed and washed. Before evisceration, the carcasses are rinsed in a pre-evisceration wash (prewash) cabinet using 32°C water mixed with peracetic acid at a desired concentration. From this step, the carcasses travel down the gut table where the removal of intestines and internal organs occurs. After evisceration, the carcasses are split into two sides and viscera are recovered as some edible products (e.g., tongue, lungs, liver, and heart) in viscera processing. The sides move to a carcass wash cabinet, where they are rinsed using 32°C water mixed with peracetic acid at a desired concentration and then continue to an organic acid spray cabinet to reduce the microbial load on the sides. The sides are then held in a chilling room where cold water is sprayed intermittently with antimicrobial agents for 24 to 48 hours at around 1°C of ambient temperature within a chilling room to control the rigor mortis process. Then the sides enter the fabrication floor where cutting and deboning occur. While the sides are fabricated into primal and sub-primal cuts, bones, fats, meat
scraps and other offal are generated and are sent to rendering process for rendering into a range of products of edible lards, bone meal, and meat meal. Finally, the products are packaged and stored in a chilled room until further distribution. All wastewater produced in the plant is treated before discharging to a local water body. Biogas is also recovered from the wastewater treatment plant and is used within the plant for replacing some purchased natural gas.

Figure 1.1 Process flow of a typical large-size beef processing facility in the U.S.
1.2 Introduction to life cycle assessment

The term “sustainability” has been described in different ways and discussed from a wide spectrum of perspectives. Generally, there are three pillars of sustainability (i.e., economy, environment, society) commonly discussed for sustainability assessment studies (Mihelcic et al., 2003). Various sustainability assessment methodologies and frameworks have been proposed to balance economic opportunities, environmental responsibility, and societal benefits of various production systems (Rodríguez-Serrano et al., 2017; Sala et al., 2015; Singh et al., 2012). Water and energy assessment is commonly applied in on-site environmental sustainability assessment of meat production (Djekic and Tomasevic, 2016). Environmental life cycle assessment (LCA) is another well-established assessment tool (International Organization for Standardization, 2006).

LCA can be used to evaluate the environmental impacts of a product, process, or services from a life-cycle perspective, including all resource inputs and emissions from raw materials extraction, transportation, manufacturing, operation, and end of life stages. It includes four fundamental steps to conduct an LCA study, including the definition of study goal, inventory data collection, selection of impact assessment method, and interpretation. Many impact assessment methods have been developed, such as TRACI v2.1 developed by USPEA and ReCiPe version 2016 created by joint efforts of multiple parties, including Leiden University and National Institute for Public Health and the Environment (RIVM) in Nederlands (Huijbregts et al., 2016).

LCA can generally be classified into three categories depending on different methods of inventory data collection, i.e., process-based, economic input-output (EIO) based, and hybrid LCA (Crawford et al., 2018; Suh and Huppes, 2005; Yu and
Wiedmann, 2018). Process-based LCA basically applies a bottom-up approach to collect inventory data of interest while the EIO-based LCA employs a top-down approach to estimate inventory data and environmental emissions from a wide range of economic activities. The process-based approach is believed to yield more accurate inventory data than the inventory data estimated from EIO-based approach. However, process-based inventory usually results in system truncations since it is almost unlikely to collect all inventory data at the process level.

The EIO-based approach estimates inventory data at a coarser resolution, typically based on available EIO databases aggregating specific industries into a general sector. The advantage of EIO-based LCA is its ability to fully capture inventory data of environmental emissions via transaction across industries, thus avoiding system truncations issues compared to traditional process-based LCA. For example, most process based LCAs do not account for the environmental impacts embedded in a wide variety of services (e.g., financial, governmental services) when manufacturing a product due to data limitations. The hybrid LCA can be considered as a combination of process-based LCA and EIO-based LCA. It is believed that hybrid LCA can quantify the environmental impacts more comprehensively compared to process-based and EIO-based by complementing system boundary truncation in process-based approach with EIO database.

1.3 Past sustainability analyses of beef processing

Life cycle assessment studies related to the beef industry have evolved in recent years. The quality of inventory data improved from coarse inventory data (Peters et al.,
towards more granular data (Mogensen et al., 2016) with temporal and spatial considerations (Rotz et al., 2019). The environmental indicators considered in the beef industry have also increased from greenhouse gas emissions (GHGs) to more environmental concerns, such as eutrophication, fossil energy, etc (Lupo et al., 2013; Asem-Hiablie et al., 2018). Most LCA studies of the beef supply chain focused on beef production on the farm stage (i.e., feed, cow-calf, feedlot) since most environmental burdens (e.g., GHGs, water footprint) occur during the farm stage (Lupo et al., 2013; Pelletier et al., 2010; Rotz et al., 2019; Stackhouse-Lawson et al., 2012). For example, around 85 – 90 % of GHGs and water footprint of the complete beef supply chain from farm to restaurant are contributed by the farm stage, including feed, cow-calf, and feedlot (Asem-Hiablie et al., 2019). Only a few LCA studies go beyond the farm stage and include beef post-harvesting (e.g., slaughtering and processing) (Mogensen et al., 2016; Peters et al., 2010), transportation, retailer, and consumer stage (Asem-Hiablie et al., 2019; Huerta et al., 2016) at the stage level. The Asem-Hiablie et al. (2019) collected inventory data from integrated farm system model simulation, industrial partners, public databases and literature to construct the life cycle inventory data for the whole U.S. beef supply chain. However, those LCAs covering the whole beef supply chain usually analyze the environmental impacts of each stage as a whole. Without understanding the environmental impacts at the process level, effective measures are difficult to implement.

Most sustainability analyses related to water and energy data in U.S. beef processing are reported in the literature on the overall plant-level. Detailed analysis of water and energy use at process level is needed to analyze the sustainability of energy and water consumption. One most recent study conducted by Ziara et al. (2016) collected
water and energy data at certain key processes (e.g., antimicrobial interventions, viscera processes). However, no studies regarding water and energy usage at detailed process-level have been performed for the U.S. beef processing industry.

Sequential antimicrobial systems in the U.S. beef processing industry are key treatments to improve the microbiological safety of beef products at the cost of intensive resource use and high-strength wastewater emissions. Most studies of antimicrobial systems in beef processing facilities in the U.S. focus on their sanitizing impacts and onsite water and energy use (Gill and Bryant, 1997; Gill and Landers, 2003; Greig et al., 2012; Ziara et al., 2016). Their environmental and economic implications have not been systematically investigated from a life cycle perspective to avoid shifting burdens. Moreover, the effectiveness of antimicrobial interventions is currently analyzed one-at-a-time, impeding the comprehension of which antimicrobial systems are in conjunction with goals for environmental and economic sustainability.

The beef slaughtering stage has been a primary focus of food safety interventions. In a surveillance report from Centers for Disease Control (CDC) for foodborne diseases outbreaks in the U.S. between 2009 and 2010, beef was the food that accounted the most foodborne outbreaks that connected food with ingredients from one of the seventeen predefined food commodities (CDC, 2013; Painter et al., 2013). minimizing pathogenic contamination on beef products within slaughterhouses is at the expense of consuming intensive resources (water, energy, chemicals, etc.) and posing occupational threats on workers safety. Scanlon et al. introduce a methodology of integrating occupational hazards into account of life cycle assessment and demonstrate it in municipal solid waste
treatment systems (Scanlon et al., 2015). However, none of studies have investigated foodborne pathogen, environmental, and occupational impacts on human health together.

Most LCA studies related to food processing industry apply traditional process-based approach to collect inventory data (Li et al., 2018a; Mogensen et al., 2016). Process-based inventory usually results in system truncations since it is almost unlikely to collect all inventory data at process level. Integrated hybrid LCA has been developed and applied in other industry systems to address this deficit (Wiedmann et al., 2011). However, those integrated hybrid LCAs are mainly focused on one or two environmental indicators (e.g., GHG, fossil fuel footprint), thus impeding our understandings on the wide spectrum of various environmental impacts available in LCA studies, such as eutrophication, human health, ecotoxicity. Moreover, none integrated hybrid LCA studies have been found for the food processing industry, let alone beef processing industry. Therefore, an integrated hybrid LCA is needed to facilitate a comprehensive understanding of the environmental impacts of U.S. beef processing industry and serve as an example for other food processing systems.

1.4 Research motivation and objectives

The Shiga toxin-producing Escherichia coli Coordinated Agricultural Project (STEC CAP) grant funded by U.S. Department of Agriculture-National Institute of Food and Agriculture (USDA-NIFA) is a multi-institutional and interdisciplinary project, including 15 institutions and 51 collaborators across the US. The STEC CAP aims to advance improving beef food safety practices and knowledge in preharvest, post-harvest, and consumer stage and enhancing the sustainability of the beef production system. This
dissertation provides a sustainability analysis for the STEC CAP project with the focus on beef processing (post-harvest) stage, mainly including beef slaughtering, processing, and packaging systems.

The overarching goal of this dissertation is to analyze the sustainability of beef post-harvest processing from multiple perspectives (economic, environmental, public health) and identify potential alternative approaches that may be more sustainable. As many assessment methods have been designed to evaluate the economic, environmental, and societal sustainability of production systems, they are not widely applied in the beef processing industry.

This study aims to address four knowledge gaps. First, a lack of onsite process-level data limits the application of sustainability assessment models. Second, the most environmental and economic analyses applied in production systems of the beef processing industry do not consider upstream and downstream activities, restricting a comprehensive understanding of its environmental and economic sustainability. Third, human health risks caused by the beef processing industry and its relative importance to other relevant risks within the beef industry (i.e. beef foodborne illness and occupational hazards) are not well understood due to methodological limitations; thus impeding effective measures on minimizing human health risks on the U.S. beef industry. Fourth, the process-based LCA has system truncation issues, which would result in missing environmental impacts due to incomplete system boundary of beef processing.

This dissertation aims at enhancing understanding of the sustainability in U.S. beef processing industry by bridging the aforementioned research gaps. The five specific objectives of this dissertation and their connections are presented in Figure 1.2:
1. To benchmark process-level water and energy data at a typical large-size beef processing plant with recommendations on efficiency measures.

2. To analyze the environmental and economic impacts of three antimicrobial systems currently applied in commercial beef processing plants.

3. To further analyze 40 common possible combinations of antimicrobial systems and incorporate meta-analysis to evaluate antimicrobial effectiveness with environmental and economic impacts.

4. To develop a unified framework to compare human health impacts caused by environmental and occupational impacts from U.S. beef slaughtering and beef foodborne illness.

5. To analyze the embedded environmental impacts of upstream systems absent in process-based LCA via an integrated hybrid LCA in beef processing.

1.5 Organization of the dissertation

Chapter 1 introduces the U.S. beef processing industry and processing steps, the application of life cycle assessment, and current status of sustainability analysis in U.S. beef processing. The key research motivations and objectives are also introduced.

Chapters 2 through 6 yield five peer-reviewed papers orderly corresponding to Objectives 1 through 5. Chapter 7 summarizes the findings of the dissertation and propose future research based on the work accomplished in this dissertation.
Overall objective: Advance the sustainability knowledge of U.S. beef processing with the focus on its antimicrobial systems

Benchmark process-level water and energy and other inventory data (Objective 1)

Impact: Served as baseline data for improvement changes comparison and inventory data for LCA modeling

Provide a portion of inventory data

Analyze environmental and economic impacts of three commercial antimicrobial systems (Objective 2)

Further analyze 40 common possible combinations of antimicrobial systems and incorporate their effectiveness via meta-analysis (Objective 3)

Impact:
1) Quantify the environmental and cost impacts of steam treatments vs chemical treatments
2) Useful to balance the tradeoffs between environmental, economic and effectiveness

Develop an unified framework to compare human health impacts caused by environmental, occupational and foodborne illness (Objective 4)

Impact: Useful to understand tradeoffs of human health impacts caused by various risks (i.e., environmental, occupational and foodborne)

Environmental impacts on human health

Develop hybrid-based LCA model and compare with process-based LCA results (Objective 5)

Impact: Useful for accounting environmental impacts embedded with background economic activities (e.g., office supplies, financial services)

Outcome:
1) Advance sustainability knowledge of beef processing industry
2) Methodologies and frameworks developed can be easily developed in other food processing industry when data becomes available

Figure 1.2 Objectives map for sustainability assessment of U.S. beef processing in this dissertation
Chapter 2

2. Assessment of water and energy use at process level in the U.S. beef processing industry: case study in a typical U.S. large-size plant

2.1 Abstract

Food processing industries consume intensive water and energy to produce food products. However, their water and energy data are scarce and require good measurement approaches. This study presents data collection and analysis of process-level water and energy use in a large-size U.S. beef processing plant through combined use of portable and in-line meters and theoretical calculations. The kill floor and plant cleaning are the primary water users, accounting for 28.7% and 24.0%, respectively. The refrigeration compressor system is the largest user of electricity, consuming 24.5% of plant-wide electricity. Heating of water for plant cleaning and food safety purposes is the largest thermal energy use in summer (81%) and second largest in winter (49.7%), with unit heating values of 625 and 666 MJ/ton live cattle weight in the summer and winter, respectively. Twice as much thermal energy is used in the winter than summer due to space heating requirements. A regression analysis found that as outdoor temperatures increased, a slight water use increase and larger energy use decrease were observed. The measurement approach can be applied to other food processing facilities and
benchmarking data can be compared to facilities elsewhere in the beef processing industry.

2.2 Introduction

The U.S. meat processing sector is the largest consumer (24%) of fresh water utilized in the food and beverage industry (Bustillo-Lecompte and Mehrvar, 2015). Water use in beef processing plants not only consumes a significant share of fresh water in its communities but also produces a high volume of slaughterhouse wastewater that contains high level of fats, blood, intestinal mucus and chemicals due to cleaning activities, resulting in high strength of wastewater (Bustillo-Lecompte and Mehrvar, 2015; Johns, 1995). However, most available data from the literature are not current with recent changes to processes in the industry and have unclear system boundaries. Moreover, no recent studies regarding water and energy usage of the U.S. beef processing industry at a full-process level have been identified in archival literature.

Energy efficiency has been highlighted in many industries worldwide as saving energy not only contributes to financial benefit but also environmental and societal sustainability, and industrial competitiveness (Therkelsen et al., 2014; Wang, 2014; Wojdalski et al., 2015). Many studies have been conducted on energy use in various food processing sectors, such as canning tomato, sugar beet, citrus packing plants (Avlani et al., 1980; Naughton et al., 1979; Singh et al., 1980). However, studies on energy use in the U.S. meat processing plants remain scarce, especially in U.S. beef processing industry. The energy use information remains limited in large beef processing plants, thus
making it difficult to evaluate their energy savings potential (Anantheswaran et al., 2014).

The beef processing industry utilizes intensive energy to convert raw materials into edible and high-value food products, consisting of processes, such as pasteurization, sterilization, evaporation, and cooling. Despite the fact that the concept of energy efficiency has been widely accepted, a trend of increasing energy use has been observed due to stricter hygiene regulations applied in the meat industry (Ramírez et al., 2006). Electricity used for beef chilling was found as a significant electricity user in slaughterhouses and has great saving potential (Gigiel and Collett, 1989). Energy consumption in the meat processing industry is plant-specific, affected by many factors such as facility size, processing technologies used, production capacity, etc. (Klemes et al., 2008; Wojdalski et al., 2013). Despite the fact that tremendous variability exists in terms of energy consumption in the meat industry, energy savings can be obtained through proper housekeeping practices and process optimization, such as insulating steam and hot water pipes, recovering waste heat from byproducts or blowdown water for boilers, optimizing motors and pumps in the desired efficiency, minimizing energy usage, etc. (Fritzson and Berntsson, 2006; Klemes et al., 2008).

Benchmarking water and energy usage is essential to diagnose hotspots of water and energy users and propose financially feasible solutions for improving sustainability. Detailed process-level water and energy data can be used as inventory data for further environmental life cycle assessment of certain food manufacturing operations, such as antimicrobial interventions during food processing (Li et al., 2018a). Meat and Livestock Australia Ltd and Australian Meat Processor Corporation have investigated water and
energy use in the red meat industry sector (i.e., cattle, lamb, goats) of Australia and provided average data every five years since 1998 and reported water use, electricity, and natural gas use (Ridoutt et al., 2015). While the global water and energy use data at plant level are useful to researchers, the lack of details on water and energy use at process level impedes progress in the development of new processes and technologies with improved energy and water use efficiencies. Therefore, research on water and energy balance at process level of the U.S. beef processing industry is a necessity.

In this study, we demonstrated a method to collect water and energy use at process level using a combination of portable and in-line meters and theoretical calculations and then reported the results in the context of the technical literature. The objectives of this study are to 1) demonstrate data collection and development of water and energy baselines at the process level using multiple data sources, and 2) propose water and energy efficiency measures. The baselines aid in understanding benefits and costs when changing commercial food manufacturing practices.

2.3 Methodology

The production activities and processes at a large-size U.S. Midwestern beef processing plant were monitored throughout the year of 2016. Several visits to the facility were conducted to map the flowchart and subsequently quantitative data of water and energy use were collected. Two factors (i.e., operating capacity and outdoor temperature) were investigated on process-level water and energy use over a seven-month period (June – December 2016) based on process-level data availability.
The plant studied operated two 8-hour shifts for processing cattle during weekdays (Mondays to Fridays) and one 8-hour shift for cleaning and sanitizing. Understanding the function of each process is fundamental in assessing water or energy use. Therefore, a detailed process flow diagram of the plant was mapped, with a simplified version illustrated in Figure 2.1. Each step of the process flow diagram was described subsequently.

2.3.1 Process-level data collection

The total water, electricity, and natural gas use were collected over the entire year of 2016 on a daily basis while process-level water and energy data were collected at various time intervals in 2016. All data were normalized per metric ton live cattle weight (t LCW) with an estimated live weight of 635 kg per cattle. The difference between overall plant water and energy use and the sum of water and energy use at processes was assigned as “unaccounted”. Although cattle were not slaughtered on weekends, water and energy were required to maintain the essential performance on weekends for the facility, such as cooling, cleaning, maintenance, and potential leaks. Therefore, the sum of water and energy use on weekends was averaged by the number of weekdays that the facility slaughters cattle on the same week and then was evenly allocated back to water and energy use on each weekday.
In this study, water data collection was accomplished by using a combination of Fuji Electric FSC portable ultrasonic flow meters (Fuji Electric Co., Ltd., Japan) and the plant’s electromagnetic in-line meters. Data from in-line meters were always obtained first when available. For other processes where in-line meters were not installed, portable ultrasonic flow meters were applied for at least one-week period. In some cases, the
portable meters were used to understand temporal water use patterns. The layout of the meter system combining portable ultrasonic meters and in-line meters in the facility is also presented in Figure 2.1. The accuracy of portable flow meters was found as 1% according to the manufacturer’s specifications. The portable flow meters were tested against in-line meters at a hydraulics lab of the University of Nebraska-Lincoln (UNL) and an error of less than 3% was observed. The accuracy of in-line meters within the plant was also verified by comparing data on the same pipe obtained by an ultrasonic meter and in-line meters over two weeks and the difference was within 5%.

Electricity data were all obtained by in-line electricity meters (Westinghouse, model IQ DATA PLUS II) installed in subprocesses (i.e., refrigeration compressor system, fabrication/packaging, engine room, slaughterhouse, rendering, wastewater treatment). Thus, electricity data collected in specific processes included all electricity use for those processes, such as lighting and all motors running in that process. Overall natural gas, biogas production and steam for processing blood were also obtained by in-line meters. The space heating was estimated by walk-through inspections identifying number, capacity, and efficiency of furnaces. The facility utilizes multiple boilers to generate steam with the pressure of 827 kPa with an 87% boiler efficiency estimated by the plant’s engineers based on an internal energy audit. The amount of heat from natural gas for supplying hot water or steam in each process was calculated using the following formula combined with the heat equation (Widder, 1976) and boiler efficiency:
\[ Q = \frac{m \times C_p \times \Delta T}{\eta_{\text{boiler}}} \]  

(2-1)

Where

\( Q \) = Thermal energy required in the process (kJ)

\( m \) = weight of water at various processes (kg)

\( C_p \) = specific heat of water (4.2 kJ kg\(^{-1}\) K\(^{-1}\)) (Tipler & Mosca, 2003)

\( \Delta T \) = change in temperature between the temperature of inlet water and desired temperature of water at various processes (K)

\( \eta_{\text{boiler}} \) = boiler efficiency, 87%

2.3.2 Evaluate impacts of operating capacity and outdoor temperature on water and energy use at processes level

Multiple linear regressions were tested to examine the impacts of two explanatory variables, operating capacity and outdoor temperature, on daily water or energy use at processes level (p-value <0.05), using the available process-level water and energy data between June 2016 and December 2016 (number of observations, n=125). Operating capacity was presented as the percentage of the maximum capacity and it ranged from 68% to 92% to maintain data confidentiality. Data on the averaged daily outdoor temperature of the plant’s location were obtained in the unit of Celsius (°C) via the online website (https://www.wunderground.com/). Stepwise regression using bi-directional elimination based on Akaike Information Criterion was applied to select variables using “step()” function in R software version 3.4.4 (R Core Team, 2018). The R-square contributions of the two variables to multiple linear regressions models were calculated
based on sequential R-square using “calc.relimp()” function from relaimpo package version 2.2-3 (Grömping, 2006) in R software. Annual U.S. industrial cost of natural gas and electricity were applied to economic estimates in this study representing a typical beef processing plant in the U.S (US EIA, 2018a, 2018b). Water supply cost was averaged by industrial water rates from eight cities in the U.S. where beef processing plants are located.

2.4 Results and discussion

2.4.1 Water usage at process level

Process-level water usage measurement of current operations are essential for guiding the design and operation of processes and facilitating comparison with newly developed water-efficient technologies. Data of process-level water use were collected by Fuji Electric FSC portable Ultrasonic flow meters and by the plant’s in-line meters. The flow rates were normalized by its highest flow rates during the period to maintain data confidentiality. Figure 2.2 a) shows the normalized flow rate of overall water entering the plant. Flow rates on weekdays decreased dramatically from midnight to 6 A.M. This is because the plant stopped processing cattle and starts sanitation cleaning shift at around midnight and finished at about 5 A.M. Flow rates on weekdays started increasing at about 6 A.M. when the plant begins processing cattle with a slight reduction at about 12 P.M., 3:30 P.M. and 9 P.M. because of meal times and shifts break for employees. It is noted that flow rates on weekends constantly remained in the range of 24 to 35% of peak flow rates to maintain essential services for the plant, such as cleaning, yards washing, water for cooling hydraulics system, water for feeding boilers and condensers, etc. An
opportunity to improve water efficiency was found by observing 43°C water use pattern using portable ultrasonic meters. The 43°C water was mainly used for washing aprons and hand washing by employees. Continuous flow rates of 43 °C water on weekends remained roughly 22% of its peak flow rates as shown in Figure 2.2 b), which was considered as undesirable water use as 43 °C water was not expected to be used on weekends. This is due to the accumulation of leaks because of worn foot valves of sinks and water facets not being turned off after use.

Figure 2.2 Average daily water use pattern. Data averaged from one week from two pipes: a) overall water inlet; b) water usage with a temperature of 43°C; note that the flow rates were normalized highest flow rates of its own pipe during the period of metering

As shown in Table 2.1, overall water usage of the plant was 4947.0 ± 374.6 L/t LCW. This amount of water use in the sector of beef processing is less than 1%
compared to the water footprint of the whole beef supply chain from a life cycle perspective (Asem-Hiablie et al., 2019; Beckett and Oltjen, 1993). However, the water use in beef processing plants is still a significant share of water consumption in its community and the resulting wastewater poses massive threats on its surrounding water bodies (Bustillo-Lecompte and Mehrvar, 2015). The cost of water is rising as less fresh water remains and the real cost of water used in the meat processing industry is more expensive when considering the cost of treating and discharging wastewater, which makes water use a more critical role in the beef processing industry (Ziara et al., 2018).

Considerable quantities of water are used for washing of livestock, products, sanitizing of process areas and equipment, and other miscellaneous usages of plant services in beef processing plants to provide essential services. No dominant water users are found but several primary users are identified from Table 2.1. Kill floor and plant cleaning being the first two primary water users, accounting for 28.7% and 24.0% of total water use, respectively, followed by rendering operations (13.1%), evisceration and viscera processing (10.9%). It is noted that 5.1% of total water use remained unaccounted due to the natural imprecision of data collection as it uses a combination of ultrasonic meters and in-line meters over different time periods and due to other minor uses such as human consumption. The holding yard utilized 5.7% of total water for rinsing the yard, cattle drinking and washing the cattle before entering the processing line. The coefficient of variance of water use in the yard is higher than other processes because water consumption in yard depends heavily on cattle’s availability on yards.
### Table 2.1 Process-level water use

<table>
<thead>
<tr>
<th>Processes</th>
<th>Description</th>
<th>Frequency of data measurement</th>
<th>Water usage (L/t LCW)</th>
<th>% of total water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yard</td>
<td>Yards washing, live cattle hide washing, cattle drinking</td>
<td>3 Shifts/day</td>
<td>247.5 69.1</td>
<td>5.0%</td>
</tr>
<tr>
<td>Kill floor</td>
<td>Hide wash and processing</td>
<td>Daily</td>
<td>82.4 16.6</td>
<td>1.6%</td>
</tr>
<tr>
<td></td>
<td>Head wash</td>
<td>1 min interval</td>
<td>136.9 11.2</td>
<td>2.8%</td>
</tr>
<tr>
<td></td>
<td>Antimicrobial interventions&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1 min interval</td>
<td>320.4 24.1</td>
<td>6.5%</td>
</tr>
<tr>
<td></td>
<td>Other cold water in kill floor&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1 min intervals</td>
<td>335.4 15.5</td>
<td>6.8%</td>
</tr>
<tr>
<td></td>
<td>Other warm water in kill floor&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Daily</td>
<td>220.6 33.4</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>Hot water used in kill floor&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Daily</td>
<td>323.1 20.3</td>
<td>6.5%</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>1418.8</strong> NA</td>
<td><strong>28.7%</strong></td>
</tr>
<tr>
<td>Evisceration and viscera processing</td>
<td>Viscera table&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1 min interval &amp; bucket estimated</td>
<td>246.2 NA</td>
<td>5.0%</td>
</tr>
<tr>
<td></td>
<td>Intestine wash and cooking; Tongue dip tank</td>
<td>1 min interval</td>
<td>131.8 NA</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>Tripe and omasum wash</td>
<td>Daily</td>
<td>159.3 23.7</td>
<td>3.2%</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>537.3</strong> NA</td>
<td><strong>10.9%</strong></td>
</tr>
<tr>
<td>Rendering</td>
<td>Edible rendering</td>
<td>Daily &amp; 1 min interval</td>
<td>155.1 24.0</td>
<td>3.1%</td>
</tr>
<tr>
<td></td>
<td>Inedible rendering</td>
<td>Daily &amp; 1 min interval</td>
<td>492.4 63.8</td>
<td>10.0%</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>647.6</strong> NA</td>
<td><strong>13.1%</strong></td>
</tr>
<tr>
<td>Chilling room &amp; fabrication</td>
<td>Cold water spray in chiller</td>
<td>Daily</td>
<td>242.9 44.8</td>
<td>4.9%</td>
</tr>
<tr>
<td></td>
<td>Hot water for sterilization</td>
<td>Daily</td>
<td>90.5 26.6</td>
<td>1.8%</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>333.4</strong> 71.4</td>
<td><strong>6.7%</strong></td>
</tr>
<tr>
<td>Plant cleaning</td>
<td>Water with HP&lt;sup&gt;e&lt;/sup&gt; at processing shifts</td>
<td>2 Shifts/day</td>
<td>553.0 117.0</td>
<td>11.2%</td>
</tr>
<tr>
<td></td>
<td>Water with HP&lt;sup&gt;e&lt;/sup&gt; at sanitizing shift</td>
<td>1 Shifts/day</td>
<td>632.5 151.1</td>
<td>12.8%</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>1185.6</strong> 199.1</td>
<td><strong>24.0%</strong></td>
</tr>
<tr>
<td>Plant services</td>
<td>Condensers; Boiler feed makeup; Boilers blowdown and pick heaters build-up washing</td>
<td>Daily</td>
<td>326.8 61.4</td>
<td>6.6%</td>
</tr>
<tr>
<td>Unaccounted human consumption, truck wash, etc.</td>
<td></td>
<td></td>
<td><strong>250.1</strong> NA</td>
<td><strong>5.1%</strong></td>
</tr>
<tr>
<td>Main water usage</td>
<td>Water at processing shifts</td>
<td>2 Shifts/day</td>
<td>3659.5 374.6</td>
<td>74.0%</td>
</tr>
<tr>
<td></td>
<td>Water at sanitizing shift</td>
<td>1 Shifts/day</td>
<td>1287.5 188.9</td>
<td>26.0%</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td>3 Shifts/day</td>
<td><strong>4947.0</strong> 374.6</td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

Note:
<sup>a</sup> Antimicrobial interventions processes include pre-evisceration wash, carcass wash, and organic acid spray cabinet.
<sup>b</sup> Temperature of warm water includes 32°C and 43°C.
<sup>c</sup> Temperature of hot water is 82°C used in the plant for knives and equipment sterilization.
<sup>d</sup> Two pipes in viscera table were estimated with a stopwatch by 4-gallon bucket due to location restrictions.
<sup>e</sup> Water with HP refers to water used at high pressure (2068 kPa) with the temperature of 60°C.

NA= Standard deviations are not available as multiple pipes were metered in different periods.

Prewash, carcass wash, and organic acid spraying are considered as conventional antimicrobial interventions processes in commercial beef processing industry aiming at
reducing pathogens, especially *E. coli* O157: H7, on beef carcass (Greig et al., 2012; Smith et al., 2013). The total water used by these three antimicrobial interventions in the kill floor (prerinsh, carcass wash, organic acid spray) is 320.4 ±24.1 L/t LCW, accounting 6.5% of overall water usage within the plant. Although water usage in these antimicrobial interventions is not the largest water consumer in the plant, the wastewater produced in these antimicrobial processes has a low pH due to the added organic acids as antimicrobial agents, which can result in malfunctions in subsequent wastewater treatment processes (Rajeshwari et al., 2000). Hot water with the temperature of 82°C in kill floor uses 6.5% of total water for knives and equipment sterilization. Currently, hot water in kill floor is overflowed through the production time in order to maintain the cleanliness of the water and to maintain the water temperature not less than 82°C as regulated by Food Safety Inspection Service, United States Department of Agriculture (USDA FSIS, 1999). Upating sterilization systems, such as installing automatic valves and temperature sensors, can therefore improve not only water use but also energy use efficiency.

Water consumption in the rendering process involves processes such as hydraulic systems, air scrubbers, cookers and soft water for centrifuge separators, accounting for 13.1% of total water. Water use of the plant cleaning at processing shifts is the 60°C water at high pressure with 2068 kPa by plant employees when necessary while cattle are processed at the same time. Water use of the plant cleaning at sanitizing shift is the 60°C water with high pressure by a cleaning crew at an overnight shift when the plant does not process cattle. Water use for plant services mainly included condensers, boiler feed makeup, and boilers blowdown and pick heaters build-up washing.
2.4.2 Energy usage at the process level

Electricity and thermal energy are the two dominant energy sources for beef processing plants. The perishable nature of beef products requires intensive energy consumption for refrigeration. The whole facility consumed 106.8±13.8 kWh/t LCW, which is much more efficient compared to a study conducted in Australia red meat industry ranging from 297 to 354 kWh/HSCW (Hot standard carcass weight) (Ridoutt et al., 2015). Figure 2.3 presents breakdown of electricity use, highlighting that refrigeration compressor system is the largest user of electricity, accounting for 24.5% of overall electricity use, followed by fabrication/packaging (18.4%), engine room (17.6%), slaughterhouse (13.9%) and rendering (11.2%) and on-site wastewater treatment processes (6.5%). Separate electric metering of each piece of equipment is not feasible, therefore electricity meters were used to measure each area (e.g., refrigeration, fabrication).

The refrigeration compressor system, including refrigeration in the chilling room and product storage and air conditioning in fabrication floor, consumes 26.2±3.6 kWh/t LCW of electricity. Electricity in fabrication and packaging is the second largest electricity user as these two processes involve lighting, ventilation, and motors of equipment (grinders, cutters, motors of conveyors, evaporators, blowers in fabrication floor, case sealers, and box makers for packaging). Engine room utilizes 18.8±2.4 kWh/t LCW, which is widely used for motors for boilers, water pumps, air compressors, etc. to provide service to other processes in the plant. Slaughterhouse, including kill floor and viscera processing, consumes 14.8±1.7 kWh/t LCW, primarily for motors of equipment
(hydraulics system, conveyors, split saws, refiners, washers, etc.), lighting and ventilation.

Figure 2.3 Process-Level electrical use (overall electricity use = 106.7 ± 13.8 kWh/t LCW)

The sources of thermal energy utilized in the facility include natural gas purchased and biogas recovered from the anaerobic wastewater treatment. As water use is closely tied to energy use especially through water heating in the food processing industry, thermal energy use profile was also evaluated. Thermal energy use for water heating ranges from 625.0 to 665.9 MJ/t LCW for food safety purposes (Table 2.2). Improving the efficiency of hot water use could not only reduce water use but also lower its associated thermal energy use. In this studied facility, the annual average energy applied for heating of process water was 255.0 MJ/1000 L. Heating the water can cost up to five times that of purchasing the influent water, based on typical U.S. natural gas prices (US EIA, 2018a) and regionally common water supply costs. Thermal energy use
in winter is the almost double amount as the thermal energy use in summer as additional natural gas is needed for space heating in winter. In summer, most thermal energy is utilized for heating water, accounting 81.0% while only 49.7% of thermal energy is for heating water in winter. Plant cleaning is the water use with the highest thermal energy use due to the large volume of the water applied.

**Table 2.2 Process-level thermal energy use**

<table>
<thead>
<tr>
<th>Processes</th>
<th>Description</th>
<th>Summer*</th>
<th>% of total</th>
<th>Winter*</th>
<th>% of total</th>
<th>Methods of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal energy by process</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water heating</td>
<td>Warm water for process(^a)</td>
<td>200.6</td>
<td>26.0%</td>
<td>218.2</td>
<td>16.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant cleaning</td>
<td>258.5</td>
<td>33.5%</td>
<td>274.6</td>
<td>20.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hot water for sterilization(^b)</td>
<td>165.9</td>
<td>21.5%</td>
<td>173.0</td>
<td>12.9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td><strong>625.0</strong></td>
<td><strong>81.0%</strong></td>
<td><strong>665.9</strong></td>
<td><strong>49.7%</strong></td>
<td>Water and thermal calculation</td>
</tr>
<tr>
<td>Space heating</td>
<td>Prevention of pathogen propagation; human comfort</td>
<td>64.8</td>
<td>8.4%</td>
<td>495.4</td>
<td>37.0%</td>
<td>Gas meter &amp; Nameplate with estimated hour</td>
</tr>
<tr>
<td>Unaccounted</td>
<td>Other usages and heat loss</td>
<td>82.2</td>
<td>10.6%</td>
<td>187.4</td>
<td>13.3%</td>
<td>Estimated</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>772.1</strong></td>
<td><strong>100.0%</strong></td>
<td><strong>1339.3</strong></td>
<td><strong>100.0%</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Thermal energy by source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchased</td>
<td>Natural gas</td>
<td>659.4</td>
<td>85.4%</td>
<td>1198.7</td>
<td>89.5%</td>
<td>Gas meter</td>
</tr>
<tr>
<td>Recovered</td>
<td>Biogas from WWTPs</td>
<td>112.7</td>
<td>14.6%</td>
<td>140.6</td>
<td>10.5%</td>
<td>Gas meter</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>772.1</strong></td>
<td><strong>100%</strong></td>
<td><strong>1339.3</strong></td>
<td><strong>100%</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
* The temperature of the overall water inlet to the plant is assumed to be 12.8°C and 15.6°C in winter and summer, respectively.
\(^a\) Warm water for process refers to warm water less than 82°C, for apron wash, hand wash, antimicrobial interventions, some of the viscera processing.
\(^b\) Hot water for sterilization refers to water with a temperature higher than 82°C.

**2.4.3 Comparison of water and energy use with previous studies**

Most of the water and energy use at the process level observed in the current study are broadly comparable with findings from other reference plants in the literature. To facilitate the comparison, all reported values were converted to the same basis (a ton of live cattle weight or t LCW). The dressing percentage, which is the ratio of carcass
weight to live cattle weight, is assumed to be 63% (Verheijen et al., 1996). Over the last 25 years, reported water usages in beef slaughtering industry around the world vary substantially, ranging from 2000 to 15000 L/t LCW (Hansen et al., 2000; Pagan et al., 2002; Ridoutt et al., 2015; Warnecke et al., 2008; Ziara et al., 2016).

Water intake reductions have been observed in the red meat industry sector (i.e., cattle, lamb, goats) of Australia decreasing from 7434 to 5418 L/t LCW between the period of 1998 and 2013/14 (Ridoutt et al., 2015). In that same study, energy efficiency improvements, that is electricity and natural use, have also been found dropping from 223 to 187 kWh/ t LCW and 958 to 572 MJ/ t LCW from 2008/09 to 2013/14, respectively (Ridoutt et al., 2015). Pagan et al. (2002) documented an eco-efficiency profile, including water and energy use, for a typical meat plant where 150 tons of HSCW were processed per day in 2002. In our study, the water use in the kill floor was 246.2 L/t LCW, which is comparable with findings (252 L/t LCW) from Pagan et al. (2002). The same situation applies to water use in plant cleaning (1185.6 L/t LCW) in this study similar with water use in plant cleaning from other two studies (982 L/t LCW from Pagan et al. (2002) and 1157 L/t LCW from Ziara et al. (2016). The water use in antimicrobial interventions (320.4 L/t LCW) from our study is also found to be close with the findings from another study reporting a similar value (369 L/t LCW) for these antimicrobial interventions (Ziara et al., 2016). This similarity may be because these three antimicrobial interventions are automatic processes, often using similar equipment across the U.S. beef processing facilities.

Differences in water and energy use with previous studies were also observed. The analyzed plant was characterized by lower water use in holding yard (247.5 L/t
LCW) compared to the reported value (1050 L/t LCW) from the Pagan et al. (2002). This might be partly attributed to additional washing needed because of the receipt of extremely dirty cattle (Pagan et al., 2002). The water used in rendering (63 L/t LCW) reported from the Pagan et al. (2002) is tenfold more efficient than the water used in this study (647.6 L/t LCW), implying that water savings opportunities may exist in the rendering process. For example, the inedible rendering consumes 492.4 L/t LWC for producing inedible tallow, meals for animal feed, etc. Optimizing water use efficiency or transitioning from wet rendering to dry rendering could result in considerable water savings. The disparity in water use of rendering can be attributed to differences in production practices and differences in byproducts made such as edible rendering products and inedible rendering products. Electricity use of the refrigeration compressor system (26.2 kWh/t LCW) in the studied plant was found more efficient, than that (30.4 kWh/t LCW) reported in another mid-size beef processing plant (Ziara et al., 2016). This can be attributed to that higher operating capacity which led to a better electricity efficiency in the storage of refrigerated products.

2.4.4 Multiple linear regression analysis of water and energy use at various processes

Multiple linear regressions were tested to examine the impacts of two explanatory variables, operating capacity and outdoor temperature, on water or energy use at processes level (p-value<0.05). With such analysis, beef processing plants can avoid confounding baseline data caused by operating capacity and outdoor temperature when the benchmark is performed in different seasons or different operating capacities. The complete data used for this analysis included only half of the year (June-December in
Lack of data especially during winter months (e.g., January, February) due to the time constraints of the project may impair the outdoor temperature analysis. More data collection covering a longer time period is suggested for future work.

Table 2.3 includes processes where data on water and energy use were available to conduct multiple linear regressions considering the two variables of operating capacity and outdoor temperature. In all regressions, the interaction term (operating capacity x outdoor temperature) was not significant, based on AIC during stepwise selection. Water use in a slaughterhouse, including kill floor and viscera processing, was not investigated due to limited data. Outdoor temperature and plant capacity did not have a considerable effect ($R^2$ less than 0.3) on water use in yard, plant cleaning and chilling room, and electricity use in fabrication/packaging.

According to the R-square contribution, the variations of the total water and total electricity regressions are explained mostly by operating capacity while the variation of thermal energy regressions is more related to the outdoor temperature. All electricity users are more strongly correlated to operating capacity than outdoor temperature except for refrigeration compressor system. To further highlight the average impacts of changes in operating capacity and outdoor temperature, two scenarios were also quantitatively analyzed for potential water and energy savings on the processes where water and energy use are affected by operating capacity and outdoor temperature with a total R-square higher than 0.40. As listed in Table 2.3, an operating capacity increase of 5% on average results in considerable reductions in water, electricity and thermal energy use with 257.3 L/t LCW, 7.5 kWh/t LCW and 94.4 MJ/t LCW, respectively. The total potential savings could be $0.96/t LCW. If the outdoor temperature rises by 10 ºC, average increases of 4.4
kWh/ t LCW of total electricity and 90.0 L/t LCW of total water would be expected. However, an average reduction of 221.5 MJ/ t LCW of thermal energy would be saved due to less demand for space heating. From the cost-wise comparison among water, electricity, and thermal energy, an increase of 10 °C of outdoor temperature could lead to a reduction of $0.34/t LCW in total costs. These results suggest that if the average local temperatures increase by 2.5°C, the current plant will use 0.5% more water but 5% less thermal energy and 1% less electricity when operating at the same operating capacity.

Table 2.3 Multiple linear regression analysis of water and energy use at various processes. Impacts on total water or energy savings are highlighted in bold.

<table>
<thead>
<tr>
<th>Processes</th>
<th>$R^2$ contributed by $X_1^*$</th>
<th>$R^2$ contributed by $X_2^*$</th>
<th>Impacts if 5% of $X_1$ increased (L, kWh or MJ)/t LCW</th>
<th>Impacts if 10 °C of $X_2$ increased (L, kWh or MJ)/t LCW</th>
<th>$/t$ LCW</th>
<th>$/t$ LCW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total water (L/t LCW)</td>
<td>0.51</td>
<td>0.08</td>
<td>-257.3</td>
<td>-0.16</td>
<td>90</td>
<td>0.06</td>
</tr>
<tr>
<td>Fabrication (L/t LCW)</td>
<td>0.23</td>
<td>0.38</td>
<td>-6.5</td>
<td>-0.004</td>
<td>-9.0</td>
<td>-0.006</td>
</tr>
<tr>
<td>Plant services (L/t LCW)</td>
<td>0.03</td>
<td>0.51</td>
<td>-9.9</td>
<td>-0.006</td>
<td>51.8</td>
<td>0.03</td>
</tr>
<tr>
<td>Yard (L/t LCW)</td>
<td>NS</td>
<td>NS</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Plant cleaning (L/t LCW)</td>
<td>0.28</td>
<td>NS</td>
<td>NA</td>
<td>NA</td>
<td>51.8</td>
<td>0.03</td>
</tr>
<tr>
<td>Chilling room (L/t LCW)</td>
<td>0.02</td>
<td>0.09</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total electricity (kWh/t LCW)</td>
<td>0.31</td>
<td>0.09</td>
<td>-7.5</td>
<td>-0.50</td>
<td>4.4</td>
<td>0.30</td>
</tr>
<tr>
<td>Engine room (kWh/t LCW)</td>
<td>0.30</td>
<td>0.23</td>
<td>-1.1</td>
<td>-0.07</td>
<td>0.8</td>
<td>0.05</td>
</tr>
<tr>
<td>Slaughterhouse (kWh/t LCW)</td>
<td>0.51</td>
<td>0.03</td>
<td>-0.7</td>
<td>-0.05</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Rendering (kWh/t LCW)</td>
<td>0.39</td>
<td>0.11</td>
<td>-0.6</td>
<td>-0.04</td>
<td>-0.1</td>
<td>-0.01</td>
</tr>
<tr>
<td>Refrigeration compressor system (kWh/t LCW)</td>
<td>0.05</td>
<td>0.59</td>
<td>-1.7</td>
<td>-0.11</td>
<td>4.0</td>
<td>0.27</td>
</tr>
<tr>
<td>Fabrication/packaging</td>
<td>0.23</td>
<td>0.06</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Thermal energy (MJ/t LCW)</td>
<td>0.21</td>
<td>0.54</td>
<td>-94.4</td>
<td>-0.30</td>
<td>-221.5</td>
<td>-0.70</td>
</tr>
</tbody>
</table>

Note:
* $X_1$=Operating capacity (%); $X_2$= Outdoor temperature (°C); NS= not significant; NA= not assessed; Negative values indicate reductions in water or energy use (L, kWh or MJ)/ t LCW and cost ($/t LCW) while positive values represent augmentation of water or energy use.
2.4.5 Summary of water and energy efficiency measures

After an evaluation of the baseline water and energy use, efficiency measures were identified. Reporting of water and energy use at the process-level allows a cost analysis to be applied to specific changes. Examples of changes implemented after collecting and analyzing the baseline data using this approach are provided below from both this facility and in other similar facilities assisted by our team. Although some expected savings might be relatively small, the aggregate impacts of these measures might be significant. In some cases, the implemented water use reduction was in the tens to hundreds of millions of gallons per year and annual cost savings from reduced water purchases, wastewater treatment, and hot water heating in the hundreds of thousands of dollars. These efficiency measures were proposed based on the combination of results from this study, onsite investigations, and published literature. The first recommendation is directly from the results of this study. The next seven recommendations are directly from our observations and interactions with the plant personnel both from this facility and in other similar meat processing plants assisted by our team. The last four recommendations are adopted from the literature. These efficiency measures are orderly listed as follows:

- Application of portable meters to measure real-time water flow rate to identify and minimize unnecessary water use. For example, Figure 2.1 demonstrates the wastage of 43 °C in weekends during which slaughtering was not performed;
- Reduction of electricity use in refrigeration compressor system by modifying compressor speed (Widell and Eikevik, 2010);
• Updating knife cleaning technologies that do not use a continuous flow of hot water;
• Application of flow restrictors and smaller nozzles on overnight cleaning hoses;
• Reduction of hot water nozzle sizes in carcass wash cabinets;
• Installation of foot pedals on previously continuous water flow devices;
• Changes of operating procedures to shut off hot water using equipment during breaks;
• Water recycling unit in specific process steps, such as the tripe wash;
• Reuse of water in chilling for hide-on-carcass wash and pre-evisceration wash cabinets;
• Reduction of product loss through changes in operational procedures, such as replacement of thermal pasteurization with antimicrobial chemical (Li et al., 2018a);
• Application of warm or hot boning to significantly save energy and water consumption during the chilling stage (Schmidt and Keman, 1974); and
• Dry cleaning yards before washing with water (Kupusovic et al., 2006).

2.5 Conclusions

Although the results of this case study were obtained from a typical U.S. beef processing facility, the measurement approach and findings can be useful elsewhere. The kill floor and plant cleaning were the two major water users, account for 28.7% and 24.0%, respectively. The refrigeration compressor system is the most significant user of electricity, accounting 24.5% of overall electricity use, followed by fabrication/packaging
(18.4%), engine room (17.6%), and slaughterhouse (13.9%). Thermal energy used for water heating varies throughout a year from 625.0 to 665.9 MJ/t LCW for food safety purposes. A regression analysis found that as outdoor temperatures increased, a slight water use increase and larger energy use decrease were found. These results broaden our understandings of factors that influence water and energy efficiency at the process level and can be helpful in developing innovative technologies for the improvement of water and energy efficiency in the beef processing industry.
Chapter 3

3. Compare environmental and economic impacts of three antimicrobial systems commercially applied in U.S. beef processing industry

3.1 Abstract

Antimicrobial systems in the U.S. beef processing industry are key treatments to improve the microbiological safety of beef products. However, product loss due to discoloration and use of chemicals, energy, and water have environmental and cost implications. This study compared environmental life cycle impacts and relative operating costs among three scenarios of antimicrobial systems currently applied in the commercial U.S. beef processing industry. Key differences between the three scenarios are the dominant use of antimicrobial chemicals, steam, and hot water pasteurization. Findings reveal that antimicrobial systems featured with chemicals result in greater human toxicity, ecotoxicity, and eutrophication impacts while antimicrobial systems featured with steam or hot water pasteurization lead to higher global warming and energy depletion. Contributions within each antimicrobial system were evaluated by: 1) seven components and 2) four intervention steps. Results show that antimicrobial chemical, wastewater treatment, and natural gas use are the three leading contributors across all environmental impacts. Evaluating environmental impact contributions of intervention
steps helps target reduction goals in primary intervention steps and reveals potential opportunities for further impact reductions. A relative operating cost analysis of each scenario found revenue loss from discolored products in antimicrobial systems applying thermal pasteurization is the most significant contributor, resulting in higher operating costs than that of antimicrobial system featured with chemicals. This study provides a systematic assessment regarding environmental and cost impacts of three scenarios of antimicrobial systems, can help guide process optimization, and provide a baseline for comparison with future new antimicrobial systems.

3.2 Introduction

According to U.S. Centers for Disease Control and Prevention (CDC), there were about 50 foodborne outbreaks of various pathogens associated with the consumption of beef products in 2016. These outbreaks resulted in three deaths, 143 hospitalizations, and over 800 cases of illness between 2010 and 2015 (CDC, 2016). Since 2010, three beef related multistate outbreaks of Escherichia coli (E. coli) O157: H7 have been investigated by the CDC, with two involving Shiga toxin-producing Escherichia coli (STEC), and the largest outbreak affecting 21 persons across 16 states in 2010 (CDC, 2010). Beef products produced from commercial beef processing plants are susceptible to contamination from cattle hides or gastrointestinal tract and cross-contamination from processing equipment, thus posing severe threats on foodborne outbreaks of beef (Stopforth and Sofos, 2006).

Consequently, minimizing pathogenic contamination of beef products is a priority in the beef processing industry. Various antimicrobial interventions in beef processing
facilities (such as pre-evisceration wash, carcass wash, organic acid spraying, hot water pasteurization, steam pasteurization, chilling at refrigerated temperature, etc.) have been found to have efficient decontamination on beef carcass (Gill and Bryant, 1997; Gill and Landers, 2003; Greig et al., 2012). Although significant sanitizing impacts of aforementioned interventions on products in beef processing facilities have been evaluated, the environmental and economic implications of waste streams and product loss due to interventions have not been systematically investigated. For example, Ziara et al. (2016) examined energy and water use in the beef industry focussing on antimicrobial interventions, and Viator et al. (2017) evaluated meat and poultry products’ safety interventions costs, and found a significant cost difference between small and large establishments.

Determining environmental impacts can be accomplished through the adoption of life cycle assessment (LCA), a tool under international standards (International Organization for Standardization, 2006) to quantify environmental impacts of a product or a system through its life cycle from raw materials extraction to materials production to its end of life, thus avoiding a shift in environmental burdens between various components across life cycle stages. Due to the rapid development of LCA, it has been applied to compare environmental impacts of various processes and systems (Amini et al., 2015; Amos et al., 2018). LCA has also been increasingly used to evaluate environmental impacts in food systems (Roy et al., 2009). A study investigating environmental impacts associated with antimicrobial medicine use within swine production facilities using EcoIndicator 99 method concluded that the use of antimicrobial medicine could improve growth rates and feed utilization and reduce
diseases, while increasing all environmental impacts due to manufacturing and use of antibiotics (Stone et al., 2011). Up to now, little research in the literature has explored environmental life cycle impacts in conjunction with economic impacts of antimicrobial systems. Examining relationships between cost and environmental impacts is essential to understand the benefits and costs of antimicrobial systems to guide researchers developing new antimicrobial interventions.

As no single antimicrobial intervention is 100% effective, multiple antimicrobial interventions are commonly combined as a sequential intervention system within current U.S. commercial beef processors. In each antimicrobial system, there are several general steps, such as pre- and post-evisceration treatments (Greig et al., 2012). A variety of interventions implemented within each step of these antimicrobial systems, featuring significant consumption of water, energy, and antimicrobial chemicals, may have a considerable variance in environmental and cost significances. The sequential antimicrobial intervention systems, using vastly different treatments, enable an examination of how the current practices may affect resource use, environmental impacts, and costs. As some innovative interventions are evolving towards more efficient and sustainable approaches in the food industry, such as electrostatic spraying (Ganesh et al., 2010; Lyons et al., 2011), developing current baseline profiles of antimicrobial systems allow the industry to use them as a baseline reference to compare with innovative antimicrobial interventions.

Beef processing plants employ various antimicrobial systems to reduce microbial load on beef carcass to meet the needs from their clients. In this study, environmental life cycle assessment and operating cost analysis were used to compare impacts of three
antimicrobial systems currently used in U.S. commercial beef processing industry. With better information, beef processors can strategically upgrade their current antimicrobial intervention practices to a more sustainable and profitable arrangement while maintaining the sanitizing effects on beef products. As the U.S. beef processing industry continues to evolve on the food safety front, this study will play an integral role in improving the sustainability of future intervention systems.

### 3.3 Methodology

#### 3.3.1 Description of the three scenarios of sequential antimicrobial systems

An antimicrobial system consists of several sequential antimicrobial interventions in the beef processing plant. The most common antimicrobial intervention steps can be categorized into four categories namely: 1) pre-evisceration wash (prewash), 2) carcass wash, 3) main treatment, and 4) chiller at an approximate refrigeration temperature of 1°C. In this study, three scenarios of the sequential antimicrobial system that are commonly found in beef processing plants in the United States are investigated as shown in Figure 3.1. It is noted that the term “main treatment” was defined in this study to refer to all interventions after carcass wash and before chilling, including hot water pasteurization, steam pasteurization, organic acid spray, etc. (Gill and Bryant, 2000; Gill and Landers, 2003). All three scenarios are currently applied in U.S. commercial beef processing plants as a part of Hazard Analysis and Critical Control Points (HACCP). Therefore, these three scenarios of antimicrobial systems were assumed to provide similar levels of microbial reductions on the beef carcass surface and meet current food safety standards.
In Scenario 1, a predominant feature is the use of antimicrobial chemicals. Both prewash and carcass wash apply a solution of 350 ppm of peracetic acid (PAA) at 32 °C instead of spraying organic acid separately. The water pressure in the prewash cabinet is around 110 kPa, while the carcass wash has a pump booster which increases water pressure to 1700 kPa to sanitize and remove loose tissue and bone dust. Main treatment employs an organic spray cabinet with a 4% lactic acid solution at 54°C. In the chiller step, beef carcasses are cooled down to 1°C and sprayed intermittently with a 120 ppm PAA solution before proceeding to the fabrication process.
Scenario 2 is found in the same beef processing plant that has same commercial settings of antimicrobial systems (i.e., same temperature, pressure and water flow rates) as Scenario 1 with modifications that feature the use of steam pasteurization and the reduction of chemical usage. The prewash and carcass wash in Scenario 2 apply the same amount of warm water wash at 32 °C as scenario 1, without the addition of PAA. A steam pasteurization cabinet is operated before the lactic acid spray cabinet to replace a certain amount of chemical use while ensuring the overall effect of pathogen reduction on beef carcasses.

Scenario 3 features the use of hot water pasteurization. The prewash recirculates 85 °C hot water in the cabinet to replace some chemical use. This is immediately followed by a spray of 5% lactic acid in a back-to-back spray cabinet. The carcass wash applies 1700 kPa high-pressure water at 38 °C to sanitize the carcass and eliminate loose tissue and bone dust. Next, the beef carcasses go through an 85 °C hot water pasteurization cabinet followed by another organic acid spray cabinet with 5% lactic acid. In the chiller step, beef carcasses are sprayed with an intermittent spray of cold water to prevent carcass from shrinking during cooling to 1 °C for around 24 hours before proceeding to fabrication.

3.3.2 Goal and scope

The goal of this study is to provide more in-depth case studies of comparative environmental and cost impacts of antimicrobial systems currently applied in the beef processing industry for sanitizing beef carcasses. From an industrial standpoint, this study can be used to support sustainable design, training, and operations of antimicrobial systems. From an academic standpoint, this study provides a framework to evaluate
sustainability into newly antimicrobial systems. The functional unit of this study was selected as 1000 kg hot standard carcass weight (HSCW). All resources inputs (e.g., water, energy, chemicals, and cabinet materials) and emissions of wastewater considered in this study were normalized by the functional unit.

For each of the three antimicrobial systems evaluated, all onsite resources and waste treatment were cataloged. Environmental life-cycle impacts were determined from raw materials extraction and production, onsite emissions, treatment of discolored meat, and treatment of wastewater. Environmental footprint of wastewater treatment was calculated by cataloging chemicals and electricity used for treatment, and downstream effluent emissions. As some of the byproducts from wastewater treatment can be used to offset the use of fertilizers and natural gases, they are considered as avoided products in the study (Figure 3.2). By developing such baselines of life cycle comparison, it ensures that improvements of antimicrobial systems do not shift burdens during their life cycle stages.

3.3.3 Life cycle inventory (LCI)

The life cycle inventory of resources, energy, and wastewater was modeled for each of three scenarios of antimicrobial systems in SimaPro software (Version 8.4, PRé Consultants, The Netherlands). The foreground data specific to this study, including water use, energy use, chemicals requirements, and wastewater treatments of each antimicrobial system were collected through plant visits, consultation with plant operators, and equipment specifications provided from vendors. Databases of US-EI 2.2 and ecoinvent unit process version 3 available in the Simaprox software were chosen as
background databases (LTS, 2016; Wernet et al., 2016). US-EI 2.2 incorporates the U.S. database into ecoinvent datasets wherever U.S. specific data is available, including U.S. production of electricity, natural gas, etc. In this study, preference was given first to unit processes from US-EI 2.2 to better reflect production activities in the U.S., and then to the ecoinvent databases. A list of unit processes chosen as life cycle inventory can be found in Supplementary Information (SI), Tables S3.1-S3.2.

Figure 3.2 Relevant components and energy flows considered in the antimicrobial systems boundary of the LCA model.

Daily cattle slaughter data were provided by two beef processing plants located in the midwestern region of the United States. Average live cattle mass was estimated as 635 kg, which is typical for plants in this region, and 62% of live cattle weight was assumed to be hot standard carcass weight (HSCW) without heads, feet, hides and internal organs (Verheijen et al., 1996). Construction inventory data of cabinets was collected through on-site physical measurement of cabinets in conjunction with the cabinet lifespan and frequency of nozzle replacement, and specifications provided by the manufacturer, Chad Equipment, LLC. Details regarding materials and mass of the cabinet
assembly can be found in SI, Table S3.3. Water use data for each antimicrobial intervention were collected for at least one week by portable ultrasonic flowmeters (Fuji Electric Co., Ltd., Japan) or by in-line electromagnetic meters installed in the plants. Discolored meat occurs in the antimicrobial systems that apply thermal pasteurization (i.e., hot water and steam pasteurization). Discolored meat is treated in inedible rendering process onsite. A unit process regarding a slaughterhouse rendering process built in ecoinvent was used to estimate the environmental impacts associated with handling of discolored meat (Table S3.4).

The required thermal energy for heating water in each cabinet was calculated using the heat equation (Widder, 1976). Electricity consumption for each antimicrobial cabinet assembly was calculated using the electric power ratings on the nameplate of the devices and the operating time duration. It is worth mentioning that the electricity used in chiller stage was assumed to be identical across the three scenarios and was not included in this study, as this study focused on a comparative perspective. Additional information regarding the breakdown of water, thermal energy, and electricity usage of each antimicrobial system can be found in SI, Tables S3.5-S3.6.

Environmental impacts associated with wastewater treatment were also evaluated in this study. Specifically, resource inputs and outputs associated with treating wastewater from the beef processing plant were provided by the wastewater treatment plant owned by a beef processing plant. All wastewater from the three antimicrobial systems were assumed to be treated in the same wastewater treatment plant, where the data was collected. In addition to overall slaughterhouse wastewater, wastewater samples were also collected from each cabinet, and the concentrations of biochemical oxygen
demand (BOD$_5$) were tested. To better account for environmental impacts associated with treating different wastewater from individual antimicrobial interventions, the wastewater equivalent for each antimicrobial intervention was calculated based on its BOD$_5$ loading as compared to the BOD$_5$ loadings of 1 m$^3$ of overall wastewater from the beef processing plants. More information on BOD$_5$ loadings from each antimicrobial intervention can be found in SI, Table S3.7. Two avoided products, natural gas and mineral fertilizer, were modeled to account for avoided environmental impacts of co-products during anaerobic wastewater treatment processes. As a typical co-product of industrial anaerobic wastewater treatment, biogas supplements a fraction of natural gas for heat production. Sludge produced by an anaerobic lagoon wastewater treatment system replaces certain amounts of commercial mineral fertilizer. The phosphorus contents in sludge produced from the wastewater treatment plant were obtained from the Enforcement and Compliance History Online (ECHO) database held by the Environmental Protection Agency (EPA). Diammonium phosphate was chosen as a reference of commercial mineral fertilizer with 20% P content (46% P$_2$O$_5$ content), available in US-EI inventory database. The methodology applied for calculating the substitution rate of sludge was adopted from Niero et al. (2014), assuming 100% of phosphorus from the sludge is bioavailable. Inventory of resource inputs, emissions, and avoided products for treating 1 m$^3$ slaughterhouse wastewater can be found in SI, Table S3.8.

Application rates and safety data sheets of antimicrobial chemicals applied in each intervention were obtained from plant operators to calculate the use of antimicrobial chemicals per functional unit. Antimicrobial chemicals are the chemicals used to reduce
microbial load or prevent microbial growth. Several antimicrobial chemicals are commonly applied in the food industry, including peracetic acid (PAA), lactic acid, acetic acid, sodium chlorite, etc. (Alvares et al., 2008). PAA and lactic acid are the two antimicrobial chemicals applied in the scenarios investigated in this study. Specifications regarding the manufacture of PAA are unavailable in the current inventory database due to proprietary confidentiality of industrial processes. Therefore, inventory for PAA production was derived based on the stoichiometric relationship in a manufacturing route (Buschmann and Del Negro, 2012). More details regarding the inventory of PAA solutions can be found in SI, Table S3.9.

Several inputs were precluded in this study since they were assumed consistent across the three antimicrobial systems. Electricity use for cooling carcass in chiller was excluded, as electricity is used for all three systems. Transportation of antimicrobial chemicals to beef processing facilities and manufacturing of cabinet assembly were also omitted as they have been predetermined as insignificant and remain consistent regardless of the antimicrobial system.

3.3.4 Life cycle impact assessment

The tool for reduction and assessment of chemical and other environmental impacts (TRACI v2.1) developed by U.S. EPA was chosen for this study as it is more relevant to the North American region (Bare, 2012). TRACI v2.1 is a midpoint-oriented environmental impact method which classifies emissions and raw materials input into ten categories, including ozone depletion, global warming, smog formation, acidification, eutrophication, carcinogen, non-carcinogen, respiratory effects, ecotoxicity, and fossil fuel depletion. In this study, normalization factors for US territory in 2008, calculated by
Ryberg et al. (2014), were applied as the reference of environmental burdens caused by an individual American per year to provide insights into the relatively significant environmental impact categories of this study.

### 3.3.5 Monte Carlo simulation and Pedigree matrix approach for uncertainty analysis

Monte Carlo simulation (MCS) was applied to capture underlying uncertainty inherent in the background inventory database and foreground inventory data collected on site. Background inventory databases applied in this study refers to US-EI 2.2 and ecoinvent unit process. Foreground inventory on-site data refers to consumption of energy and materials for each antimicrobial system and emissions of wastewater treatment downstream. The application of MCS addresses statistical uncertainty within antimicrobial systems, aiding better understanding of the bounds for life cycle impact categories.

The underlying probability distributions from the background database were obtained from US-EI 2.2 and ecoinvent unit process database. Uncertainties associated with the on-site resource inputs (e.g., water, natural gas, antimicrobial chemicals, and wastewater BOD₅ loadings) collected from commercial beef processing facilities were estimated using qualitative assessments of data quality based on the pedigree matrix. The uncertainties of specific inputs or outputs usually cannot be determined from the available information due to limits of data source availability. For example, some specific inputs or outputs can only be obtained as mean values or a few data points that are not sufficient to estimate their distribution and standard deviation. In this context, the
pedigree matrix approach is used as a simplified standard approach to quantify the uncertainties of these values (Ciroth et al., 2016; Muller et al., 2016).

The uncertainty of data using the pedigree matrix approach is quantified based on five criteria: 1) reliability, 2) completeness, 3) temporal correlation, 4) geographic correlation, and 5) further technological correlation. Each criterion has five quality levels with a score ranging from 1 to 5 that can be chosen based on the practitioners’ judgment on data they collected. After finishing the data quality judgment based on these five criteria, the geometric standard deviation will be calculated based on the scores of these five criteria. Uncertainty factors of pedigree matrix based on expert judgments embedded in SimaPro 8.4 were adopted in this study. More details on how to apply the pedigree matrix approach to estimate uncertainty can be found in the studies of Ciroth et al. (2016) and Muller et al. (2016). The distribution results were calculated using MCS by 1,000 random samplings and were plotted in Figure 3.3 with error bars at 95% confidence intervals.

3.3.6 Operating cost analysis

To understand potential tradeoffs of cost and environmental implications of antimicrobial systems, relative operating costs were collected and analyzed, including costs of antimicrobial chemicals, water supply, electricity, natural gas, revenue loss and wastewater treatment. Capital costs of cabinet assemblies were not included as it had been found to be very trivial based on prices provided by vendors compared to other operating expenses. The unit costs of antimicrobial chemicals (i.e., lactic acid and PAA solutions) were obtained from chemical purchasing order records of the plants. Average industrial water rates from six Midwest cities in U.S. where large beef processing plants
are located was averaged to reflect the situation of U.S. industrial water rates. Annual U.S. industrial rates of natural gas and electricity were obtained from the U.S. Energy Information Administration to represent antimicrobial systems in the U.S (US EIA, 2018b, 2018a).

Revenue loss occurs due to discolored meat caused by pasteurization (i.e., hot water and steam pasteurization). Discolored meat is trimmed and sent through the inedible rendering operation and sold as meat meal for animal consumption. The meat discoloration is negligible in antimicrobial systems that do not apply pasteurization. To estimate the value of unaffected meat (i.e., meat not discolored by pasteurization), the price of the meat as top-inside round was selected based on personal interviews with plant employees and experts in meat science to represent an average value for different types of cuts in a carcass. Revenue loss refers to the difference of value between discolored meat and unaffected meat. To estimate the average product loss, discolored meat from six split carcasses were collected and weighted as 1.5 kg per 1000 kg HSCW. Values of meat meal ($0.27/kg) and top inside round ($4.80/kg) were used to represent product loss and obtained from Daily Beef Reports by the Agricultural Marketing Service, USDA for the year of 2017 (USDA AMS, 2018a, 2018b).

To reflect typical beef processing wastewater treatment costs for the region, the industrial sewage rate structures from six U.S. Midwestern cities containing large beef processing plants were examined. These were used to estimate the six-city average cost based on both the unit charge by volume (i.e., dollar per cubic meter of wastewater) and the surcharge for treating extra strength sewage (i.e., extra strength of BODs). Dissolved air flotation (DAF) has been widely used as a pretreatment process for slaughterhouse
wastewater and the BOD₅ removal rate from DAF have been reported ranging from 32% to 92% (Al-Mutairi et al., 2008; Johns, 1995). To be conservative on the estimation, it was assumed that 50% of BOD₅ removal could be achieved by DAF before the wastewater is sent to the public wastewater treatment plant.

3.4 Results and discussion

3.4.1 Normalized environmental impacts comparison

Environmental impacts from LCA studies need a common reference to aid interpretation. Normalization helps to scale various environmental categories from a system per functional unit according to the annual environmental emissions shared by per capita on average. Results of the normalized life cycle impact assessment for the three alternative antimicrobial systems are illustrated in Figure 3.3. For example, a value of 0.01 equals to 1% of environmental impact caused by an individual American in the reference year of 2008 (Ryberg et al., 2014). Ranges of error bars represent the variability of each antimicrobial system at 95% confidence intervals via Monte Carlo simulation. The wide ranges of error bars shown in some impact categories might result from aggregation of a large number of unit processes involved in the underlying inventory database. Large variabilities in some impact categories are usually observed in LCA studies given that LCA studies deal with numerous unit processes in underlying databases (Hasik et al., 2016; Thiel et al., 2015). Due to the overlapping of error bars in some categories, such as ozone depletion, respiratory effects, smog, acidification, carcinogen, and ecotoxicity, it may be indecisive to conclude which alternative is superior to another as their uncertainties are overlapped. On the contrary, impact categories such as non-
carcinogen, eutrophication, global warming, and fossil fuel depletion indicate that differences exist between three alternatives even though uncertainties are high. The error bars are not symmetric around the mean value, because the underlying variables are assumed to be log-normally distributed. All following analysis in this study is pertinent to mean values.

According to food availability data provided by Economic Research Service (USDA ERS, 2018), the per capita consumption of beef in the U.S. is 40.3 kg beef as equivalent carcass weight. A value of 0.012 of carcinogen environmental impact for Scenario 1 equates to 1.2% of carcinogen impact caused by an individual American per year for improving sanitation safety of 1000 kg of beef carcasses. For a safe consumption of 40.3 kg of beef carcass, the environmental impacts caused by antimicrobial systems described in Scenario 1 will cause 0.048% of carcinogen shared by an American in the year of 2008. On average, the impacts of carcinogen, non-carcinogen, ecotoxicity, and eutrophication were found to be the four most significant environmental impacts for all three scenarios. For the remaining impact categories, global warming and fossil fuel depletion are relatively less significant, while ozone depletion, respiratory effects, smog formation, and acidification have trivial contributions to the overall environmental impacts.
As discussed previously, PAA and lactic acid are the two antimicrobial chemicals applied to reduce the microbial load on beef carcasses. A tradeoff in different environmental impact categories occurs between antimicrobial systems featured with chemicals and those with thermal pasteurization. On average, Scenario 1 has the highest impacts for all four major environmental impacts (i.e., carcinogen, non-carcinogen, ecotoxicity, and eutrophication) likely due to its high consumption rates of antimicrobial chemicals and resultant increase in wastewater strength. Specifically, Scenario 1 applies PAA mixed with water in the intervention steps of prewash and carcass wash, while the other two scenarios do not apply any antimicrobial chemicals in prewash and carcass wash. Scenarios 2 and 3 which feature either steam or hot water pasteurization, respectively, typically have higher impacts of global warming and fuel depletion, as they require intensive use of natural gas for heating water.
3.4.2 Components contribution

The individual contributions of supporting components to environmental impacts in each alternative are illustrated in Figure 3.4. The data were classified into seven components: wastewater treatment, antimicrobial chemicals, natural gas use, electricity use, cabinet assembly, and water use. All environmental categories defined in TRACI v2.1 method are included. For each impact category, the scenario with the highest impacts was assumed as a baseline of comparison at a value of 100%. Detailed environmental impact results by seven components can be found in the SI Table S3.10.

As illustrated in Figure 3.4, antimicrobial chemicals, wastewater treatment, and natural gas use are the three dominant contributors across all environmental impacts. Combination of antimicrobial chemicals and natural gas account for almost 100% of fossil fuel depletion and 60 to 86% of global warming due to the intensive energy required for upstream chemical production and on-site heating of water. Antimicrobial chemicals are responsible for much of carcinogen and ecotoxicity impacts, accounting for 40 to 63% and 47 to 58%, respectively. This is due to upstream emissions from antimicrobial chemicals production and resulting residual landfill materials along the production process of chemicals, such as lactic acid and peracetic acid. Last, the non-carcinogen impact is dominated by downstream wastewater treatment due to emissions of heavy metals from sludge into the soil (e.g., zinc), ranging from 82 to 89% among the three antimicrobial systems.
The eutrophication category is primarily impacted by downstream wastewater treatment which accounts for about 83% due to nitrogen and phosphorus emitted to the receiving water body (Kalbar et al., 2013). Scenario 1 tends to have the biggest eutrophication impact, suggesting higher antimicrobial chemical use can indirectly result in producing higher wastewater strength. It is worth noting that the anaerobic wastewater treatment process recycled biogas on site and was estimated to replace 19.5 MJ of natural gas per m$^3$ wastewater treated for an on-site steam boiler, thus holding a positive impact on fossil fuel depletion. This amount of recycled biogas is in the same magnitude as 47 MJ of natural gas per m$^3$ reported in the Foley et al. (2010) study that similarly applied anaerobic treatment for high strength industrial wastewater (4000 mg/L of COD as wastewater influent). Because wastewater treatment shows positive impacts on fossil fuel
depletion as it recycles biogas to replace a certain amount of natural gas, innovative wastewater treatment technologies are recommended. For example, microbial fuel cells and microbial electrolysis cells that produce electricity and hydrogen, respectively, could be considered to work alongside with anaerobic treatment systems to reclaim more energy and reduce overall wastewater treatment impacts.

The environmental impacts associated with treating 1.5 kg discolored meat per 1000 kg HSCW in the rendering process was negligible accounting less than 2% of overall environmental impacts associated with treating 1000 kg HSCW in antimicrobial systems across all impact categories (Figure 3.4). However, the resource inputs and emissions for producing 1.5 kg HSCW are not trivial throughout the life cycle of beef systems, including phases of farming. Rotz et al. (2015) reported that an average of 18.3 kg CO₂ was produced and 51.0 MJ was consumed in the production of 1 kg of carcass weight from the cradle to farm stage. The average environmental impacts associated with treating 1000 kg HSCW across the three antimicrobial systems in this study are 20.0 kg CO₂/1000 kg HSCW and 34.1 MJ of fossil fuel/1000 kg HSCW, which are considerably lower than the environmental footprints for producing 1.5 kg of beef on farm stage. This comparison from a life cycle perspective highlights the importance of product loss and suggests that the beef processing industry should optimize pasteurization systems with appropriate temperature and water use to reduce product loss without compromising antimicrobial efficacy.

Strategies for reducing environmental burdens for the three antimicrobial systems vary as major contributions come from different components for different scenarios. For Scenario 1, developing greener antimicrobial chemicals, reducing chemical use, and
recycling water containing antimicrobial chemicals could be highly beneficial to improving overall sustainability and cost efficiency, as Scenario 1 uses the most antimicrobial chemicals. For example, recirculating water from the chiller containing 120 ppm of PAA to the prewash step which requires 350 ppm of PAA, can lower chemical use and wastewater loads. For antimicrobial systems that apply pasteurization (Scenarios 2 and 3), minimizing product loss and reducing thermal losses are essential for lowering their overall environmental burdens and costs. Findings from components contribution also provide directions on the development of new antimicrobial systems, such as minimizing the use of antimicrobial chemicals through electrostatic spray technologies.

### 3.4.3 Intervention steps contribution

By analyzing the impacts of four intervention steps (prewash, carcass wash, main treatment, and chiller) within each antimicrobial system, their relative contributions to the overall impacts was identified (Figure 3.5). For each impact category, the scenario with the highest total impact was assumed as a baseline of comparison at a value of 100%. Detailed environmental impact results by four intervention steps are presented in the SI Table S10. Studies on sequential antimicrobial systems have shown improved antimicrobial efficacy on beef carcasses, emphasizing the importance of investigating overall antimicrobial efficiency combining sequential interventions (Koohmaraie et al., 2005).
For Scenarios 1 and 2, carcass wash and main treatment dominate most impact categories, accounting for at least 75% of individual impacts as a combination, due to the large consumption of water and chemicals or natural gas for heating water and producing steam. Conversely, the prewash acts as another important contributor across all impact categories in Scenario 3. This is likely due to the use of an 85°C hot water wash and a lactic acid spray in the prewash of Scenario 3. Compared to the chillers in the other two other scenarios, the chiller in Scenario 1 has the largest impacts upon ecotoxicity, eutrophication, and human health, and has the largest significance across all impact categories. This is likely a result of the application of a 120 ppm PAA solution during spraying in the chiller in Scenario 1, resulting in increased wastewater loadings, as
opposed to an intermittent water spray chill without any chemicals in the other two scenarios.

By analyzing the individual contributions of the four sequential antimicrobial interventions, it identifies the intervention steps with the highest environmental impact, thus providing directions on where strategies should focus on reducing overall environmental impacts. In addition, it reveals the potential environmental benefits of reusing waters from relatively clean intervention steps, such as main treatment and chilling, for relatively unclean intervention steps, such as prewash or interventions outside the studied system boundary but within the same facility, such as hide-on wash.

3.4.4 Comparison of relative operating costs

A comparison of relative operating costs between the three scenarios of antimicrobial systems is illustrated in Figure 3.6. Several fundamental assumptions are made to simplify the cost comparison: 1) same labor requirements for the three scenarios; 2) trivial and similar capital and maintenance costs of antimicrobial cabinets for the three scenarios and microbial tests; 3) equal costs of developing and validating HACCP plans among three scenarios. As the goal of this cost comparison is to identify the costs distinctly different among three scenarios of antimicrobial systems, these similar costs mentioned above are not included in this analysis. It is also worth mentioning that revenue loss and wastewater treatment cost were taken into account to systematically evaluate the actual cost difference between antimicrobial systems. An average product loss weight was measured at 1.5 kg per 1000 HSCW based on a sample of six carcasses due to steam pasteurization and it is assumed that hot water pasteurization causes the same amount of product loss.
Scenario 1 has the lowest cost of approximately $6.49/1000 kg HSCW since it does not result in product loss due to discolored meat (Figure 3.6). Costs are similar between Scenarios 2 and 3, with costs of approximately $10.17/1000 kg HSCW and $10.57/1000 kg HSCW, respectively, due to a large product loss cost due to discoloration issues; note that both scenarios have a lower cost of water, energy and antimicrobial chemicals than Scenario 1.

In comparing Scenario 1 to Scenarios 2 and 3, a trade-off appears between costs associated with consumption of antimicrobial chemicals and natural gas. This is due to the fact that the efficiency of antimicrobial intervention primarily relies on the temperature of hot water or steam in the absence of antimicrobial chemicals. The effectiveness of hot water is often compared with that of antimicrobial chemicals in the commercial settings. Water supply costs remained relatively constant across all three scenarios. Scenario 3 recirculates hot water in prewash and main treatment, thus requiring
more electricity due to more pumps involved, but it is still minimal compared to overall costs. Combining the results of the environmental assessment and cost analysis of the three antimicrobial systems, provides evidence that antimicrobial systems featured with chemicals tend to have lower costs with reduced impacts of global warming and energy demand, but higher impacts of human health and eutrophication, compared to antimicrobial systems featured with pasteurization.

3.4.5 Limitations and future work

It is recommended that future researchers investigate antimicrobial efficacy alongside environmental and cost impacts on sequential antimicrobial systems for a more holistic analysis, as beef safety is the top priority compared to environmental and cost concerns. In this study, equivalent antimicrobial efficacy was assumed among three alternatives as they all meet current standards. However, different pathogenic reduction might exist among the three distinct antimicrobial systems. There might be potential trade-offs between antimicrobial intervention efficiency, operating costs, and environmental impacts when designing and updating existing antimicrobial intervention strategies. Such an analysis can possibly be done by performing a meta-analysis of pathogenic risk assessment on sequential antimicrobial systems and integrating the environmental and cost impacts.

Another opportunity for ongoing research is to consider performing quantitatively sustainable design of sequential antimicrobial systems. Only a selected set of three antimicrobial systems was evaluated in this study, but other beef processing facilities may use other antimicrobial systems. As mentioned in this study, there are four general discrete intervention steps involved in commercial beef processing facilities, including
prewash, carcass wash, main treatment, and chiller. Within each separate intervention step, multiple options can be applied, such as hot water pasteurization, steam pasteurization, and different antimicrobial chemicals. With a broad range of possible combinations, opportunities promisingly exist that some combinations are predestined to be better than others in the perspectives of environmental and cost performance, without compromising antimicrobial efficacy. Up to now, antimicrobial systems have been analyzed one at a time, restricting the knowledge of which antimicrobial systems have the most environmental and cost benefits. By evaluating the environmental and cost impacts of a wide range of antimicrobial system designs, it would facilitate the research, development, and deployment of antimicrobial systems for food safety.

3.5 Conclusions

To our knowledge, the present study is the first attempt to evaluate environmental and cost implications of food-safety antimicrobial systems from a life cycle perspective. Results from normalized environmental impacts show tradeoffs exist between the three antimicrobial systems. Antimicrobial system featured with chemicals (Scenario 1) results in higher environmental impacts of human health, ecotoxicity, and eutrophication, while antimicrobial systems featured with pasteurization (Scenarios 2 and 3) lead to higher global warming and energy depletion.

By evaluating components contributions among the three antimicrobial systems, it highlights areas for improvement in each scenario. It is found that a combination of antimicrobial chemical, wastewater treatment, and natural gas use dominates across all environmental impacts. Specifically, results show that antimicrobial chemical use is
significant to carcinogen (40 to 63%) and ecotoxicity impacts (47 to 58%); wastewater treatment dominates eutrophication (about 83%) and non-carcinogen impacts (about 82 to 89%); natural gas use is as a major contributor to global warming (60 to 86%) and fossil fuel depletion (almost 100%). For Scenario 1, developing greener antimicrobial chemicals, reducing chemical use, and recycling water containing antimicrobial chemicals play essential roles in improving its environmental sustainability and cost efficiency. For Scenarios 2 and 3, minimizing product loss and reducing thermal losses can be the critical steps to improve overall environmental and economic sustainability. By evaluating intervention steps contributions, it reveals potential opportunities for reducing environmental impacts by reusing water from relatively clean intervention steps (main treatment and chilling) in relatively unclean intervention steps such as prewash.

Findings from cost comparison reveal that Scenario 1 featured with antimicrobial chemical was found to be more cost efficient since it does not result in product loss ($3.68 to $4.08 /1000 kg HSCW more cost-efficient compared to Scenarios 2 and 3, respectively). Combining the results of the environmental assessment and cost analysis of the three antimicrobial systems, antimicrobial systems featured with chemicals tend to have lower costs with reduced impacts of global warming and energy demand, but higher impacts of human health and eutrophication, compared to antimicrobial systems featured with pasteurization.
3.6 Appendix: Supporting information

3.6.1 List of background database, modeling wastewater treatment plant, manufacturing peracetic acid (PAA) solutions

Inventory of unit processes contains the resource inputs and emissions outputs from the raw material extraction, manufacturing, and transportation of each process. In this study, preference was given first to the database of US-EI 2.2 unit processes, a modified database of ecoinvent to better reflect production activities in the U.S. (LTS, 2016). For processes that were not available in US-EI 2.2 LCI database, unit processes in the ecoinvent (version 3) database were selected (Wernet et al., 2016). Inventory of the wastewater treatment process was modeled based on plant-specific data from a typical industrial wastewater treatment plant specifically treating cattle slaughterhouse wastewater to closely estimate environmental impacts associated with industrial wastewater treatment.

<table>
<thead>
<tr>
<th>Inventory data</th>
<th>Process description</th>
<th>LCI database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water supply</td>
<td>Tap water, at user/US- EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Natural gas, burned in boiler condensing modulating &gt;100kW/US-US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Electricity</td>
<td>Electricity, at Grid, US, 2008 NREL/RNA U U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Steel, low-alloyed, at plant/US- EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>Lactic acid {RER}</td>
<td></td>
</tr>
<tr>
<td>Discolored meat</td>
<td>Slaughterhouse waste {CH}</td>
<td></td>
</tr>
</tbody>
</table>
Table S3.2 List of the dataset used for modeling wastewater treatment plant

<table>
<thead>
<tr>
<th>Inventory data</th>
<th>Process description</th>
<th>LCI database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>Chlorine, gaseous, lithium chloride electrolysis, at plant/GLO US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Sodium hydroxide</td>
<td>Sodium hydroxide, 50% in H2O, production mix, at plant/US-US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Biogas, flare</td>
<td>Refinery gas, burned in flare/GLO US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Sodium hydrogen sulfide</td>
<td>Sodium hydrogen sulfite {RER}</td>
<td>production</td>
</tr>
<tr>
<td>Polyamines</td>
<td>Polyacrylamide {GLO}</td>
<td>production</td>
</tr>
<tr>
<td>Sludge, land applied</td>
<td>Sludge from pulp and paper production {RoW}</td>
<td>treatment, landfarming</td>
</tr>
</tbody>
</table>

Table S3.3 List of the dataset used for manufacturing peracetic acid (PAA) solutions

<table>
<thead>
<tr>
<th>Inventory data</th>
<th>Process description</th>
<th>LCI database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Electricity, at Grid, US, 2008 NREL/RNA U U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Thermal energy</td>
<td>Natural gas, burned in boiler condensing modulating &gt;100kW/US-US-EI U</td>
<td>US-EI 2.2</td>
</tr>
</tbody>
</table>

3.6.2 Inventory of cabinets, water, energy, and chemicals use for production of 1000 kg HSCW

Materials type and weight of cabinet assemblies were obtained from cabinet specifications provided by Chad Equipment, LLC, a company specializing in antimicrobial intervention equipment for meat processing industry. Data of main treatment of S2 and S3, including the steam pasteurization cabinet and organic acid spray
cabinet were not available. Therefore, onsite measurements were conducted to estimate the weight of cabinets.

Table S3.4 Estimated weight, service life, and materials of cabinets assembly

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Process</th>
<th>Material</th>
<th>Weight (kg)</th>
<th>Service life (years)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Prewash</td>
<td>Stainless steel</td>
<td>3783</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>Stainless steel</td>
<td>3175</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>Stainless steel</td>
<td>4283</td>
<td>20</td>
<td>Onsite measurement</td>
</tr>
<tr>
<td>S2</td>
<td>Prewash</td>
<td>Stainless steel</td>
<td>3783</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>Stainless steel</td>
<td>3175</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>Stainless steel</td>
<td>7458</td>
<td>20</td>
<td>Onsite measurement</td>
</tr>
<tr>
<td>S3</td>
<td>Prewash</td>
<td>Stainless steel</td>
<td>7008</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>Stainless steel</td>
<td>3175</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>Stainless steel</td>
<td>9026</td>
<td>20</td>
<td>Chad Equipment, LLC</td>
</tr>
</tbody>
</table>
Table S3.5 Inventory of water, energy, and chemicals use for 1000 kg HSCW

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Process</th>
<th>Water (L/1000 HSCW)</th>
<th>Electricity (kWh/1000 HSCW)</th>
<th>Natural gas (MJ/1000 HSCW)</th>
<th>Chemical type/name</th>
<th>Chemical usage (g/1000 HSCW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>PW</td>
<td>71.3</td>
<td>0.26</td>
<td>5.8</td>
<td>PAA solutions</td>
<td>106.2</td>
</tr>
<tr>
<td></td>
<td>CW</td>
<td>424.4</td>
<td>0.74</td>
<td>34.4</td>
<td>PAA solutions</td>
<td>632.1</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>19.8</td>
<td>0.05</td>
<td>3.8</td>
<td>Lactic acid</td>
<td>845.0</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>370.5</td>
<td>NA</td>
<td>0</td>
<td>PAA solutions</td>
<td>189.2</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>886.0</td>
<td>1.06</td>
<td>44.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>PW</td>
<td>71.3</td>
<td>0.26</td>
<td>5.8</td>
<td>No chemical</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CW</td>
<td>424.4</td>
<td>0.74</td>
<td>34.4</td>
<td>No chemical</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>19.8</td>
<td>0.05</td>
<td>102.8</td>
<td>Lactic acid</td>
<td>845.0</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>370.5</td>
<td>NA</td>
<td>0</td>
<td>No chemical</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>886.0</td>
<td>1.06</td>
<td>143.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>PW</td>
<td>84.5(^1)</td>
<td>0.63</td>
<td>70.3(^1)</td>
<td>Lactic acid</td>
<td>409.5</td>
</tr>
<tr>
<td></td>
<td>CW</td>
<td>296.1</td>
<td>0.74</td>
<td>32.8</td>
<td>No chemical</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>122.9(^1)</td>
<td>0.41</td>
<td>161.6(^1)</td>
<td>Lactic acid</td>
<td>409.5</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>269.2</td>
<td>NA</td>
<td>0</td>
<td>No chemical</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>772.7</td>
<td>1.78</td>
<td>264.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PW = pre-evisceration wash; CW = carcass wash; MT = main treatment;
\(^1\) Water and steam supply in the pre-evisceration wash and carcass wash of S3 was obtained from cabinet model specifications and then steam supply was used to calculate the amount of natural gas needed to produce the corresponding steam supply.

Wastewater samples were collected from each cabinet and overall wastewater and concentrations of BOD\(_5\) from each process were tested. As can be seen from Table 6, the BOD\(_5\) concentrations from various processes considerably differed. To better account the environmental impacts associated with treating different wastewater from those antimicrobial intervention process, wastewater equivalent for each process was calculated based on its BOD\(_5\) loading as compared to the BOD\(_5\) loadings of 1 m\(^3\) overall slaughterhouse wastewater (1121 mg BOD\(_5\)/m\(^3\) overall slaughterhouse wasteawter).
3.6.3 Thermal energy and electricity use for production of 1000 kg HSCW

Table S3.6 Breakdown of thermal energy use for production of 1000 kg HSCW

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Process</th>
<th>Specific heat capacity (kJ/kg °C)</th>
<th>Changes in temperature (°C)</th>
<th>Thermal energy(^1) (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Prewash</td>
<td>4.2</td>
<td>16.4</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>4.2</td>
<td>16.4</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>4.2</td>
<td>38.8</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>4.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S2</td>
<td>Prewash</td>
<td>4.2</td>
<td>16.4</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>4.2</td>
<td>16.4</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>2712.1 (steam)*</td>
<td>84.4</td>
<td>98.9</td>
</tr>
<tr>
<td></td>
<td>Main treatment (lactic acid rinse)</td>
<td>4.2</td>
<td>38.8</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>4.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S3</td>
<td>Prewash (hot water pasteurization)</td>
<td>4.2</td>
<td>69.4</td>
<td>68.6</td>
</tr>
<tr>
<td></td>
<td>Prewash (lactic acid spray)</td>
<td>4.2</td>
<td>44.4</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>4.2</td>
<td>22.4</td>
<td>32.8</td>
</tr>
<tr>
<td></td>
<td>Main treatment (hot water pasteurization)</td>
<td>4.2</td>
<td>69.4</td>
<td>159.9</td>
</tr>
<tr>
<td></td>
<td>Main treatment (lactic acid spray)</td>
<td>4.2</td>
<td>44.4</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>4.2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*2712.1 kJ/kg is the energy required to produce 1 kg of saturated steam at 827 kPa using water of temperature 15.6 °C.
\(^1\) Boiler efficiency is assumed to 85%.

Types and number of equipment and their power rating were inventoried to estimate electricity usage of each antimicrobial intervention as illustrated in Table 5.

Electricity consumption for each of the antimicrobial cabinet assemblies was calculated using the electric power ratings on the nameplate of the devices and the operating time duration.
Table S3.7 Breakdown of electrical energy use for production of 1000 kg HSCW

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Process</th>
<th>Items (# of items)</th>
<th>Equipment power rating (kW)</th>
<th>Time (h)</th>
<th>Electrical energy (kWh)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prewash</td>
<td>Oscillation motor (2)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td>S1</td>
<td></td>
<td>Exhaust blower (2)</td>
<td>11.4</td>
<td>0.009</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air door blower (1)</td>
<td>3.7</td>
<td>0.009</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>Water pump (2)</td>
<td>37.3</td>
<td>0.009</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oscillation motor (2)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>Exhaust blower (1)</td>
<td>5.6</td>
<td>0.009</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Prewash</td>
<td>Oscillation motor (2)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td>Exhaust blower (2)</td>
<td>11.2</td>
<td>0.009</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air door blower (1)</td>
<td>3.7</td>
<td>0.009</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>Water pump (2)</td>
<td>37.3</td>
<td>0.009</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oscillation motor (2)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>Air door blower (1)</td>
<td>3.7</td>
<td>0.009</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exhaust blower (1)</td>
<td>5.6</td>
<td>0.009</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Prewash</td>
<td>Water pump (3)</td>
<td>11.2</td>
<td>0.009</td>
<td>0.33</td>
</tr>
<tr>
<td>S3</td>
<td></td>
<td>Oscillation motor (2)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exhaust blower (2)</td>
<td>11.2</td>
<td>0.009</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air door blower (2)</td>
<td>3.7</td>
<td>0.009</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>Water pump (2)</td>
<td>37.3</td>
<td>0.009</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oscillation motor (2)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>Water pump (1)</td>
<td>11.2</td>
<td>0.009</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oscillation motor (1)</td>
<td>0.4</td>
<td>0.009</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exhaust blower (2)</td>
<td>11.4</td>
<td>0.009</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air door blower (2)</td>
<td>3.7</td>
<td>0.009</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*Assume 92% of electrical motor efficiency

### 3.6.4 Wastewater BOD<sub>5</sub> loadings and modeling of wastewater treatment plant

Wastewater samples were collected from each cabinet and overall wastewater and concentrations of BOD<sub>5</sub> from each process were tested. As can be seen from Table 6, the BOD<sub>5</sub> concentrations from various processes considerably differed. To better account the environmental impacts associated with treating different wastewater from those antimicrobial intervention process, wastewater equivalent for each process was calculated.
based on its BOD\textsubscript{5} loading as compared to the BOD\textsubscript{5} loadings of 1 m\textsuperscript{3} overall slaughterhouse wastewater (1121 mg BOD\textsubscript{5}/m\textsuperscript{3} overall slaughterhouse wastewter).

Table S3.8 Wastewater BOD\textsubscript{5} loadings from each antimicrobial intervention for production of 1000 kg HSCW

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Process</th>
<th>BOD\textsubscript{5} concentration (mg/L)</th>
<th>Wastewater (L/1000 HSCW)</th>
<th>BOD\textsubscript{5} loadings (g BOD)</th>
<th>Wastewater equivalent (L/1000 HSCW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Prewash</td>
<td>1437</td>
<td>71.3</td>
<td>102.5</td>
<td>91.4</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>1891</td>
<td>424.4</td>
<td>802.5</td>
<td>715.9</td>
</tr>
<tr>
<td></td>
<td>Main treatment</td>
<td>29717</td>
<td>19.8</td>
<td>588.4</td>
<td>524.9</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>774</td>
<td>370.5</td>
<td>286.8</td>
<td>255.8</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td><strong>1780.2</strong></td>
<td><strong>1588.0</strong></td>
</tr>
<tr>
<td>S2</td>
<td>Prewash</td>
<td>644</td>
<td>72.0</td>
<td>46.4</td>
<td>41.8</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>434</td>
<td>428.7</td>
<td>186.1</td>
<td>167.6</td>
</tr>
<tr>
<td></td>
<td>Main treatment (steam pasteurization)</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Main treatment (lactic acid rinse)</td>
<td>29717</td>
<td>20.0</td>
<td>594.3</td>
<td>535.5</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>671</td>
<td>374.2</td>
<td>251.1</td>
<td>226.3</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td><strong>1077.9</strong></td>
<td><strong>971.3</strong></td>
</tr>
<tr>
<td>S3</td>
<td>Prewash (hot water pasteurization)</td>
<td>428</td>
<td>76.8</td>
<td>32.9</td>
<td>29.3</td>
</tr>
<tr>
<td></td>
<td>Prewash (lactic acid spray)</td>
<td>27574</td>
<td>7.7</td>
<td>212.3</td>
<td>189.4</td>
</tr>
<tr>
<td></td>
<td>Carcass wash</td>
<td>740</td>
<td>296.1</td>
<td>219.1</td>
<td>195.5</td>
</tr>
<tr>
<td></td>
<td>Main treatment (hot water pasteurization)</td>
<td>2026</td>
<td>115.2</td>
<td>233.4</td>
<td>208.2</td>
</tr>
<tr>
<td></td>
<td>Main treatment (lactic acid spray)</td>
<td>27574</td>
<td>7.7</td>
<td>212.3</td>
<td>189.4</td>
</tr>
<tr>
<td></td>
<td>Chiller</td>
<td>300</td>
<td>269.2</td>
<td>80.8</td>
<td>72.0</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td><strong>990.8</strong></td>
<td><strong>883.4</strong></td>
</tr>
</tbody>
</table>

Environmental impacts associated with a wastewater treatment plant using an anaerobic lagoon to treat wastewater coming from beef slaughterhouse was evaluated. The resources inputs and by-products were obtained from the plant’s records. Enforcement and Compliance History Online (ECHO, https://echo.epa.gov/) held by Environmental Protection Agency (EPA) provides monthly measurements of effluent
characteristics for most of the WWTPs in the United States. The plant-specific effluent pollutant loadings, including BOD$_5$, TSS, NH$_3$, and phosphorus, were retrieved from the ECHO database through the year of 2016.

Table S3.9 Resources input and emissions associated with a typical industrial anaerobic wastewater treatment plant for treating 1 m$^3$ wastewater

<table>
<thead>
<tr>
<th>Resource input</th>
<th>Value</th>
<th>Unit</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>1.29</td>
<td>kWh/m$^3$ wastewater</td>
<td>Plant record, 2016</td>
</tr>
<tr>
<td>Chlorine</td>
<td>18.41</td>
<td>g/m$^3$ wastewater</td>
<td>Estimated from plant personnel</td>
</tr>
<tr>
<td>Sodium hydroxide</td>
<td>0.01</td>
<td>g/m$^3$ wastewater</td>
<td>Estimated from plant personnel</td>
</tr>
<tr>
<td>Sodium hydrogen sulfite</td>
<td>0.02</td>
<td>g/m$^3$ wastewater</td>
<td>Estimated from plant personnel</td>
</tr>
<tr>
<td>Polyacrylamide polymer</td>
<td>0.10</td>
<td>g/m$^3$ wastewater</td>
<td>Estimated from plant personnel</td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD$_5$, effluent</td>
<td>5.90</td>
<td>g/m$^3$ wastewater effluent</td>
<td>ECHO, EPA, 2016</td>
</tr>
<tr>
<td>TSS, effluent</td>
<td>12.20</td>
<td>g/m$^3$ wastewater effluent</td>
<td>ECHO, EPA, 2016</td>
</tr>
<tr>
<td>NH$_3$, effluent</td>
<td>0.32</td>
<td>g/m$^3$ wastewater effluent</td>
<td>ECHO, EPA, 2016</td>
</tr>
<tr>
<td>Phosphorus, total [as P]</td>
<td>18.00</td>
<td>g/m$^3$ wastewater effluent</td>
<td>ECHO, EPA, 2016</td>
</tr>
<tr>
<td>Sludge</td>
<td>514.35</td>
<td>g of dry solids/m$^3$ wastewater treated</td>
<td>Plant record, 2016</td>
</tr>
<tr>
<td>Biogas flare</td>
<td>18.18</td>
<td>MJ/m$^3$ wastewater</td>
<td>Plant record, 2016</td>
</tr>
<tr>
<td><strong>Avoided products</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>19.50</td>
<td>MJ/m$^3$ wastewater</td>
<td>Equivalent calculations</td>
</tr>
<tr>
<td>Fertilizer (diammonium phosphate)</td>
<td>75.87</td>
<td>g/m$^3$ wastewater</td>
<td>Equivalent calculations</td>
</tr>
</tbody>
</table>

### 3.6.5 Inventory of peracetic acids (PAA) solutions manufacturing route

PAA (CAS NO. 79-21-0) is an effective antimicrobial disinfectant approved by U.S. FDA and is commonly used in the meat industry as a carcass surface sanitizer.

Commercial PAA is usually made in solutions that contain peracetic acid, acetic acid, and hydrogen peroxide to maintain its stability. In this study, the PAA solutions contain 23.5% of peracetic acid, 60% of acetic acid, 10% of hydrogen peroxide and 6.5% of
water. Since the environmental impacts associated with PAA solutions, which was a key antimicrobial chemical in this study, are currently not available in the Ecoinvent database, inventory for PAA production was derived based on the stoichiometric relationship in a manufacturing route (Buschmann and Del Negro, 2012) as described below:

\[ \text{C}_2\text{H}_4\text{O}_2 + \text{H}_2\text{O}_2 \rightleftharpoons \text{C}_2\text{H}_4\text{O}_3 + \text{H}_2\text{O} \]

As emissions inventory of acetic acid and hydrogen peroxide are available in the Ecoinvent database, the emission inventory of PAA can be then extracted. It should be noted that electricity and thermal energy required for manufacturing PAA were obtained based on the work of Kim and Overcash (2003). Electricity is used for mechanical equipment and reactors, while thermal energy is used for heat sources in reactors in chemical facilities for producing PAA solutions.

Table S3.10 Inventory of peracetic acids (PAA) solutions manufacturing route

<table>
<thead>
<tr>
<th>Raw materials and energy input</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid (in water)</td>
<td>785.5</td>
<td>g</td>
</tr>
<tr>
<td>Hydrogen peroxide (in water)</td>
<td>205.1</td>
<td>g</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.0008</td>
<td>kWh</td>
</tr>
<tr>
<td>Thermal energy (natural gas)</td>
<td>0.008</td>
<td>MJ</td>
</tr>
<tr>
<td><strong>Product output (1000 g of PAA solutions)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAA</td>
<td>235.0</td>
<td>g</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>600</td>
<td>g</td>
</tr>
<tr>
<td>Hydrogen peroxide</td>
<td>100</td>
<td>g</td>
</tr>
</tbody>
</table>
### Table S3.11 Detailed environmental impact results by components

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Scenario</th>
<th>Antimicrobial chemical</th>
<th>Natural gas use</th>
<th>Wastewater treatment</th>
<th>Electricity use</th>
<th>Cabinet assembly</th>
<th>Water use</th>
<th>Discolored meat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens, CTU(h)</td>
<td>S1</td>
<td>3.5E-07</td>
<td>2.1E-08</td>
<td>1.3E-07</td>
<td>5.7E-09</td>
<td>2.0E-09</td>
<td>4.1E-08</td>
<td>0.00E+00</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>1.7E-07</td>
<td>6.8E-08</td>
<td>8.2E-08</td>
<td>6.0E-09</td>
<td>2.6E-09</td>
<td>4.2E-08</td>
<td>4.24E-09</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>1.6E-07</td>
<td>1.3E-07</td>
<td>6.8E-08</td>
<td>9.6E-09</td>
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4. Integrating environmental and economic assessment with food safety effectiveness for antimicrobial systems in U.S. beef processing

4.1 Abstract

This study aims to minimize environmental and economic impacts while providing microbial safe meat through the arrangement of sequential antimicrobial systems in the U.S. beef processing industry via an integrated life cycle assessment framework. Forty sequential antimicrobial systems were proposed and evaluated from three perspectives: microbial load reduction, environmental, and economic impacts, by meta-analysis, life cycle assessment, and operational cost analysis orderly. The results show that the antimicrobial systems applying steam pasteurization during the main intervention offer high microbial load reduction. Environmental and economic analyses reveal that human and ecosystem toxicity, eutrophication and global warming are the main contributors to the overall environmental impacts while antimicrobial chemicals, wastewater treatment, and natural gas are the three major drivers of operational cost. Devalued (discolored) meat due to contact with heat from steam pasteurization or hot water wash has a considerable increase in environmental and economic impacts. Certain antimicrobial systems (e.g., water wash followed by steam pasteurization) were found to be more promising with satisfactory effectiveness, better environmental and cost
performance under uncertainty (1,000 Monte Carlo simulations). Results from this study can guide the U.S. beef processing industry to advance sustainability while ensuring food safety and ultimately benefit our environment while protect human health from foodborne illness.

4.2 Introduction

The effective integration and resolution of the food-energy-water nexus are critical for long-term sustainability. A key aspect of food production is food safety, ensuring that the resulting product is safe for consumption. According to In the USA, 1 in 6 people become ill every year from eating contaminated food (CDC, 2015). Various combinations of antimicrobial interventions (e.g., hot water wash, steam pasteurization, and organic chemical spray) are applied by U.S. beef processors to ensure safe food by reducing the microbial load on beef carcass, thus protecting consumers’ health (Gill and Landers, 2003; Koohmaraie et al., 2005). Antimicrobial treatments are applied at different steps such as after dehiding, after splitting carcass, and after removing gut for effective overall microbial reduction. However, these antimicrobial interventions provide microbial reductions at the cost of high environmental and economic impacts (Li et al., 2018a). Microbial intervention processes use significant quantities of antimicrobial chemicals and energy (for thermal processing) which impact the environmental from the overall life cycle production, use, treatment, and discharge with key indicators such as human toxicity, ecosystem toxicity, eutrophication and global warming. A critical challenge is identifying which combinations of antimicrobial interventions offer better microbial load reductions at low environmental and operation costs.
The microbial load reduction, or effectiveness, of an intervention is often a major deciding factor for implementation (USDA FSIS, 1996). Zhilyaev et al. (2017) applied a systematic review and meta-analysis (SR and MA) on all peer-reviewed articles published for cattle slaughterhouse interventions to estimate the effectiveness of various antimicrobial interventions. The SR and MA process gathers all relevant studies together to create a more robust estimate of intervention effectiveness to allow comparison of processes. The SR and MA method can be taken a step further and attempt to explain variations among different study results through meta-regressions. In meta-regressions, characteristics of the experimental design are taken as covariates and their linear impact on the dependent variable, or intervention effectiveness, are measured. For instance, several studies testing a water wash with different temperatures, application times, and indicator organisms can be analyzed collectively, and the effect of each covariate quantified. Together, SR and MA are powerful tools in a variety of fields, where robust conclusions can be drawn from a range of literature findings (Greig et al., 2012; O’Connor et al., 2014).

Life cycle assessment has been widely integrated with social-economic analysis and other models (e.g., biochemical model) to comprehensively evaluate the sustainability of certain technologies (e.g., soil remediation strategies) or systems (e.g., cropping systems) (Song et al., 2018; Tabatabaie et al., 2018). However, integrated assessment of food safety, environmental sustainability, and operational cost of antimicrobial systems in beef processing plants has been lacking. Potential trade-offs might exist between antimicrobial intervention effectiveness, environmental impacts, and operational cost. In addition, the effectiveness of antimicrobial interventions is currently
analyzed one-at-a-time, impeding the comprehension of which antimicrobial systems (sequence of antimicrobial interventions at various processing steps) can achieve sufficient microbial load reduction in conjunction with goals for environmental and economic sustainability. During processing, cattle are first stunned and undergo a series of sequential processes of hide removal, evisceration, chilling, fabricating, and packaging. During those processes, multiple sequential antimicrobial interventions are applied to reduce bacterial contamination from hides and intestines as well as cross-contamination between processes. A more detailed description of sequential antimicrobial interventions is provided separately in the Methodology.

The objective of this study is to employ an integrated assessment framework to facilitate the development of sustainable antimicrobial interventions. Specifically, this study evaluates the sequential antimicrobial system designs from three perspectives: 1) microbial load reduction for food safety, 2) environmental impacts, and 3) operational cost. To this end, 40 unique antimicrobial systems that can be applied by the industry are analyzed. These 40 systems are various combinations of interventions applied in the three sequential steps (i.e., pre-evisceration wash, carcass wash, and main intervention).

4.3 Methodology

4.3.1 Configurations of the 40 proposed antimicrobial systems

In this study, we define “antimicrobial system” as the combination of three sequential treatments during three processing steps namely pre-evisceration wash, carcass wash, and main intervention. Pre-evisceration wash is the step immediately after the removal of hides. In general, the meat of a healthy animal is sterile. However, hides are
exposed to dirt and manure and may have a large microbial load. During dehiding, there is a high potential for microorganisms to transfer from hides to carcass. Therefore, pre-evisceration wash is performed immediately after dehiding to reduce microbial load. Carcass wash occurs directly after a carcass has been split in half and eviscerated. Before sending a carcass into the chilling room, another intervention defined as “main intervention” is applied to further minimize microbial load reduction on carcass. Many alternative interventions can be applied in each step, including water wash with a variety of temperatures, steam pasteurization, and various antimicrobial chemicals wash or spray. The antimicrobial interventions proposed in this study and their inventory data collection are based on their applications in commercial U.S. beef processing facilities. Specifically, four alternatives for pre-evisceration wash, two alternatives for carcass wash, and five alternatives for main intervention are chosen based on the data availability as shown in Figure 4.1. A detailed description of each antimicrobial intervention in each step is provided in Supporting Information (SI), Table S4.1. To this end, a total of 40 antimicrobial systems are proposed as potential applications that can be applied immediately in commercial beef processing plants with minor changes to piping and the chain lines moving the carcasses.
4.3.2 Meta-analysis on microbial load reduction for various antimicrobial interventions

The meta-regressions on antimicrobial interventions used in beef processing plants from Zhilyaev et al. (2017) were used directly to model intervention effectiveness in this analysis (Zhilyaev et al., 2017). The full-variable regressions for lactic acid, water wash, and the full-trial carcass meta-regression from the meta-analysis estimated effectiveness of lactic acid, water wash, steam pasteurization, and peroxyacetic acid (SI, Table S4.2). For lactic acid and water wash, the meta-regressions equations modeling intervention effectiveness as log CFU/cm² were directly applied as shown in Equation (1) and (2), respectively.

\[
\log \left( \frac{N}{N_0} \right)_{\text{water wash}} = -1.22 + 0.27 \cdot N_0 + 0.02 \cdot T + 0.013 \cdot t \tag{4-1}
\]

Where \( N \) is the current microbial concentration in log CFU/cm², \( N_0 \) initial microbial starting concentration or level of contamination immediately before...
intervention application in log CFU/cm² and log (N/No) is the log reduction, T is the application temperature in Celsius, and t is the application duration in seconds. The effect of temperature, time, and concentration of lactic acid within the range of 2 to 8% were not found to be statistically significant for lactic acid in the original meta-analysis. The lactic acid equation was modeled as:

$$\text{Log } (N/No)_{\text{lactic acid}} = -0.27 + 0.36 \times N_0$$ (4-2)

To model peroxyacetic acid (PAA) and steam pasteurization (SP), the existing equations were adapted as no meta-regression for PAA or SP were available due to data limitations. In these cases, IMC was assumed to be the most influential variable and linear regression was calculated on existing data for PAA and SP. Accordingly, the PAA and SP equations are built with fewer data and their effectiveness is more uncertain. For peroxyacetic acid the reductions were modeled as:

$$\text{Log } (N/No)_{PAA} = -0.69 + 0.56 \times N_0$$ (4-3)

Where the intercept and slope were calculated through a linear regression of available PAA trials (Ellebracht et al., 2005; King et al., 2005). Similarly, steam pasteurization was modeled as:

$$\text{Log } (N/No)_{SP} = 1.09 + 0.48 \times N_0$$ (4-4)

Where the parameters for the intercept and slope were calculated through a linear regression of three steam pasteurization papers (Minihan et al., 2003; Phebus et al., 1997; Retzlaff et al., 2004).

The effect of initial microbial concentration was included in all models because it was shown to have the most consistent and impactful effect on log reductions (Zhilyaev et al., 2017). For this analysis, the initial contamination before any intervention was set to
5 log CFU/cm². This value was considered representative of the data used in the original meta-regressions, as an analysis of starting concentrations showed an average of 5.02 log CFU/cm²; the 2.75% and 97.5% quantiles of the initial concentrations were 2.8 and 7.0, respectively (Zhilyaev et al., 2017). Meta-regression equations applied in this study were provided in SI, Table S4.3.

4.3.3 Environmental and economic analyses

Life cycle assessment has been widely used to quantify environmental impacts associated with various food processing systems from a lifecycle viewpoint (Barbosa et al., 2017). Process-based life cycle assessment (LCA) and operational cost were used to quantify the environmental and economic impacts of the forty proposed antimicrobial systems (Figure 4.2). The life cycle inventory of unit processes in each intervention was compiled in SimaPro v8.4 (PRé Sustainability, the Netherlands) and the functional unit of each antimicrobial system was chosen as 1000 kg of hot standard carcass weight (1000 kg HSCW). The U.S. Environmental Protection Agency’s TRACI v2.1 was chosen as the life cycle impact assessment method for this study because of its relevance to U.S. geographic region (Bare, 2012). TRACI v2.1 includes ten environmental categories: global warming, fossil fuel depletion, acidification, eutrophication, ecotoxicity, carcinogen, non-carcinogen, smog formation, ozone depletion, respiratory effects. Note that these impacts include the upstream production and manufacturing of the chemicals and other resources themselves as well as their use during and after food processing. The inventory data of direct resources use of water, energy, chemicals consumption and wastewater treatment of each individual intervention were largely obtained from studies that conducted in-depth data collection and analysis at the process level of U.S. beef
processing plants (Li et al., 2018a, 2018b; Ziara et al., 2018, 2016). The background data (e.g., electricity production, chemical production) were chosen from US-EI and Ecoinvent version 3 available in software SimaPro v8.4 (LTS, 2016; Wernet et al., 2016). More specific foreground and background data for each intervention are provided in SI, Tables S4.1 and S4.5, respectively. The environmental impacts for growing 1 kg beef meat from cradle to farm stage were obtained from a life cycle assessment study in U.S. Great Plains beef production systems (Lupo et al., 2013) and converted to environmental categories consistent with TRACI v2.1 (SI, Table S4.6).

![System boundary and scope of the integrated assessment of antimicrobial systems in the study](image)

To evaluate relative significance of various environmental impacts for antimicrobial systems, the environmental impacts were normalized to the annual environmental impacts per capita in the US (Ryberg et al., 2014). To facilitate the comparison of environmental impacts across different categories, weighting factors from the Methodology Report prepared by Sustainable Minds (SM) (Meijer, 2013) consistent
with the TRACI 2.1 environmental impact categories were applied to aggregate all environmental categories into a single score expressed in millipoint (mPt) (Table S4.7). The weight factors assign different coefficients to reflect the different importance of the ten environmental categories from TRACI v2.1. One point (1 Pt, equivalent to 1,000 mPt) refers to annual environmental burden in the U.S. per capita and therefore the higher single score implies higher environmental impacts.

In this study, the operational cost includes water, electricity, natural gas, antimicrobial chemicals and wastewater treatment. Revenue loss due to devalued (discolored) meat from exposure to high temperatures is defined as the price difference between beef cutout value and meat meal value, both estimated from Daily Beef Reports by the Agricultural Marketing Service (AMS) (USDA AMS, 2018b, 2018a). The “beef cutout value” is a mixture value from a range of primal cut values, including rib, chuck, round, loin, etc. The meat that is not discolored can be sold as beef cutout value, a much higher value than discolored meat that is sold as meat meals. The unit cost (e.g., resource inputs, wastewater treatment) was obtained from multiple sources, including governmental websites and plant operators (Li et al., 2018a). Cost breakdown of each intervention can be found in SI, Table S4.8. The maintenance and capital cost of antimicrobial systems are excluded as they are minimal when they are normalized by 1000 kg HSCW over the 20 years of lifespan and they also remained the same among various antimicrobial systems.

4.3.4 Assumptions and uncertainty analyses

To explore the robustness of results, we evaluated how the results might vary due to the assumptions and uncertainty of key variables. The impacts of two assumptions
(i.e., the amount of devalued meat caused by discoloration and the selection of weighting coefficients) were evaluated. No universal agreement on the amount of devalued meat on carcass as it varies from plant-to-plant complex practices and customer-to-customer requirements. The discolored meat is furthered processed as rendered products (e.g., pet food) or processed meat (e.g., cooked sausage) dependent on plant’s logistics and capabilities. Environmental and economic impacts of no devalued meat and 0.1% devalued meat from hot water wash and steam pasteurization were assigned to evaluate the environmental and economic profile of the 40 antimicrobial systems, based on on-site data collection and consultations with a group of experts from animal and meat science at the University of Nebraska-Lincoln. Two weighting schemes were compared to understand the impacts of different weighting coefficients on decision-making, one weighting scheme developed by SM and one weighting scheme that simply sums up normalized value across all environmental categories with equal weighting coefficient (Meijer, 2013).

The uncertainty of the amount and cost of onsite inventory data (e.g., water, energy, chemicals, wastewater) was evaluated using Monte Carlo analysis (1,000 iterations). Previous data analysis found variations in the onsite resource usage rates (e.g., water use) are within 10% of mean value and costs of most resources varied less than 20% over the past five years (Li et al., 2018b; US EIA, 2018a). To be conservative on estimation, 20% of mean value is used as one standard deviation assuming a normal distribution in the Monte Carlo analysis. Pairwise comparisons of the 40 antimicrobial systems were adopted to evaluate how results would change relatively among the 40 antimicrobial systems (Mendoza Beltran et al., 2018). Specifically, we compare the result
of system j with system k per Monte Carlo iteration, thus evaluating whether system j is better than system k based on stochastic outcomes.

4.4 Results and discussion

4.4.1 Sequential microbial load reduction

This study is intended as a comparative evaluation of the 40 proposed combinations of antimicrobial systems. The absolute microbial load reduction must be considered very carefully and requires further validation in a pilot scale before it can be applied to commercial beef processing facilities. The findings provide informative suggestions for process engineers and microbiologists when they develop new antimicrobial systems in the meat processing industry, environmental engineers as they consider needed water and wastewater treatment capacity, and the management team who is focused on reducing the cost of operation. The sequential microbial load reduction also could be integrated into food safety risk assessments (Smith et al., 2013; USDA FSIS, 2002).

Figure 4.3 shows incremental microbial load reduction of alternative treatments through the three sequential steps (i.e., prewash, carcass wash, and main intervention) with the initial microbial concentration being 5 log CFU/cm², which is representative in the meta-regressions (Zhilyaev et al., 2017). In Figure 4.3, the x-axis indicates the two steps where carcass is treated while the y-axis shows the quantitative microbial load concentration remained on carcass after the treatment of each step. Figure 4.3A presents four alternatives in the first step (Prewash). Hot water wash (HW), peracetic acid wash (PAA) and warm water wash followed by lactic acid spray (WW-LA) have similar high
efficiency, achieving to around 2.9 CFU log/cm² reduction from the initial concentration of 5 CFU log/cm². PAA and WW-LA possess similar microbial load reductions in the step of prewash and PAA has lower cost and environmental impacts ($0.50, 0.62 mPt) compared to that of WW-LA ($2.14, 1.35 mPt). However, PAA is still under evaluation of European Food Safety Authority (EFSA) and not currently approved to be used as an antimicrobial chemical on meat carcass in the European market (EFSA Panel on Biological Hazards (BIOHAZ), 2014). Furthermore, as stated earlier, there is less robust data available on PAA effectiveness than WW or LA. These results could be used to stimulate additional studies on PAA as an antimicrobial chemical.

Figure 4.3B displays two interventions in the second step (carcass wash). Warm water wash mixed with PAA has higher microbial load reduction than warm water wash (WW) alone. The combination of WW+PAA have similar microbial load reduction with HW+WW. However, the combination of HW+WW only applies water and is more beneficial in terms of cost and environment impacts when applying HW+WW ($0.85, 0.88 mPt) than WW+PAA ($3.13 and 1.53 mPt) in the first two sequential steps (prewash and carcass wash). For the main intervention step (Figure 4.3C), steam pasteurization followed by lactic acid spray (SP-LA) and SP alone were found to have similar and highest microbial load reduction, suggesting that the intervention of SP is more advantageous than SP-LA from the cost and environmental perspectives. Lactic acid spray (LA) alone generally has the least effectiveness in this step and has significantly higher cost and environmental impacts compared to SP ($2.02 vs $0.31, 1.08 mPt vs 0.34 mPt). This suggests that LA is more efficient when the microbial load concentration on
the beef carcass is higher. This finding could be especially useful for food process engineers when designing antimicrobial systems to avoid redundant interventions.

Figure 4.3 Sequential microbial load reduction from the three steps, (a) Pre-evisceration wash (Prewash), (b) Carcass wash, and (c) Main intervention

An optimal univariate k-means cluster analysis was performed on the overall microbial log reduction (SI, Figure S4.1) (Wang and Song, 2011). Three clusters were identified. Fourteen of the antimicrobial systems formed the cluster with the highest
reductions. All the log reductions were greater than 4.82 and all the systems used some version of SP (with or without an acid) as the main intervention option. Ten of the systems formed the cluster with the lowest reductions. These log reductions ranged from 2.66 to 3.65. None of these systems used SP, and only two used HW as the main interventions – most of them used organic acids. The intermediate cluster, with log reductions ranging from 3.85 to 4.44, generally used a version of HW as the main intervention. Only two used SP, and these only had WW as both the prewash and carcass wash.

4.4.2 Environmental impact assessment

The environmental performance of alternative interventions from the three sequential steps was synthesized in environmental single score based on Sustainable Minds (SM) methodology (Meijer, 2013). The SM methodology normalizes and weights the environmental impact categories derived from TRACI v2.1 to facilitate comparisons of various alternatives. Figure 4 shows a breakdown of environmental single score and comparison within each step with x-axis being the alternative treatments from each step and y-axis being their corresponding environmental single scores. Carcinogen, noncarcinogen and ecotoxicity, eutrophication, global warming, and fossil fuel depletion are the top six contributors to the environmental single score, accounting for 84-95% among all interventions. This finding is consistent with another previous study that evaluated three scenarios of antimicrobial systems (Li et al., 2018a). Recall that the life cycle of the chemicals (e.g., PAA and LA) used in the intervention can result in impacts related to human toxicity due to its upstream chemical manufacturing. The chemical use in antimicrobial systems also have higher ecotoxicity and eutrophication impacts and also
result in high strength wastewater that further requires more resources for the downstream wastewater treatment. In addition, the wastewater effluents have considerable influence on the life-cycle eutrophication impact while the land-applied wastewater sludge also contributes to the human toxicity and ecotoxicity.

![Figure 4.4 Environmental single scores of different interventions](image)

In the step of pre-evisceration wash, WW-LA has the highest environmental impacts due to the use of lactic acid and downstream treatment of its high strength wastewater. Peracetic acid wash in the step of carcass wash leads to a much higher environmental score compared to water wash only. HW-LA has the highest environmental score (2.37 mPt) among five intervention alternatives in the step of main intervention because of its high demand for natural gas for heating water and lactic acid for chemical decontamination. SP has the least environmental impacts among the five alternatives because of no chemicals and negligible wastewater.
In the rightmost bar of Figure 4, the environmental score of beef from cradle to farm stage obtained from an LCA study in U.S. Great Plains beef production systems from cradle to farm is presented (Lupo et al., 2013). The potential devalued meat (1 kg per 1000 kg HSCW) due to discoloration could occur when hot water wash or steam pasteurization is applied. The environmental single score of beef in the farm stage have higher environmental impacts than all intervention alternatives except for HW-LA. This comparison emphasizes the significance of devalued meat and urgent research on minimizing devalued meat as developing new antimicrobial systems.

4.4.3 Economic analysis

The breakdown of operational cost from different interventions from the three sequential steps is presented in Figure 4.5. Several key assumptions are made to facilitate the cost comparison, including the same cost for labor, maintenance, and developing and validating the hazard analysis and critical control points (HACCP) approach for all interventions. Wastewater treatment cost and devalued meat are included as those two components have been found to be key factors for cost profiles of interventions. Two antimicrobial chemicals (i.e., peracetic acid and lactic acid) have similar cost and are the most significant cost except for PAA in the pre-evisceration wash. The pre-evisceration wash applies much less water compared to the water used in carcass wash and main intervention, thus requiring less peracetic acid mixed with water.
The wastewater treatment cost is generally higher than water supply cost due to extra BOD$_5$ surcharge rates and relatively cheap water supply cost in Midwest, especially in the interventions that apply chemicals that lead to high BOD$_5$ concentration in the wastewater. In the step of pre-evisceration wash, WW-LA has the highest cost ($2.14/1000$ kg HSCW) due to the use of lactic acid that accounts 87% of the total cost. The same trend is also found in the step of carcass wash that 73% cost of peracetic acid wash are from peracetic acid chemical. In the step of main intervention, three interventions that applied either LA (HW-LA, SP-LA, and LA) have a higher cost than the other two interventions that only apply thermal pasteurization (HW or SP). Although
steam requires additional latent heat for vaporization, hot water wash consumes more natural gas than steam pasteurization because of the high volume of water used.

As mentioned earlier, devalued meat on beef carcass refers to the value difference between beef cutout value and by-product value estimated from USDA AMS. If not considering the impacts of devalued meat, PAA in the step of carcass wash is the most expensive single intervention among all interventions due to a significant amount of water and peracetic acid chemicals applied and wastewater treatment cost. If considering the impacts of devalued meat, HW-LA is the highest single intervention among all interventions as HW-LA consumes a high amount of natural gas, lactic acid and results in devalued meat due to hot water wash.

4.4.4 Interactions among environmental impacts, costs, and food safety

Figure 4.6 is a bubble plot that illustrates the 40 systems analyzed for the combined environmental impacts, economic operating costs, and overall microbial reductions when devalued meat from heat interventions is included. The size of the point indicates the log microbial reduction, and the color indicates the intensity of the thermal treatment that may lead to devaluated meat. Points in the upper right corner indicate high costs and high environmental impacts. Larger points in the lower left corner of the plot illustrate high microbial reductions with low impacts. In general, environmental impact is positively correlated with operational cost. However, the microbial log reductions (point size) does not consistently increase with increasing operational cost and environmental impact. Systems with LA as the final step produce the lowest microbial load reduction while systems including steam in the final step have the highest microbial load reduction generally. There is not a significant increase in microbial log reduction for adding
chemicals along with hot water or steam, but there is an increase in cost and environmental impact.

Figure 4.6 Bubble plot of interactions among environmental impacts, operational costs (assuming 0.1% devalued meat occurred), and microbial log reductions for the 40 systems studied.

There are clearly preferred options. Three systems, all featuring steam pasteurization, have relatively low operational costs and environmental impacts, with log reductions greater than 4 log CFU/cm². The log reduction of WW+WW+SP, although
located in Cluster 2, the log reduction (i.e., 4.44 log CFU/cm^2) is closer to the upper range of Cluster 2 (i.e., 4.82 log CFU/cm^2), thus considered as one of three desired systems. The HW+WW+SP and the PAA+WW+SP had log reductions of 4.84 and 4.91, with impacts of 2.98 and 3.17 mPt/1000 kg, and costs of 5.69 and 5.85 $/1000 kg HSCW, respectively. These intervention systems are both effective and more sustainable, and merit further investigation.

Inventory data used for estimating the environmental and cost performance have inherent uncertainty, thus limiting the results from Figure 4.6. A pairwise comparisons of the 40 antimicrobial systems was conducted to test the robustness of relative environmental and economic performance under uncertainty using Monte Carlo simulations (1,000 runs). A color gradient from white to red is used to demonstrate the relative environmental and cost performance of pairwise antimicrobial systems under uncertainty (SI, Figure S4.2). A pure red cell means that among 100% of 1,000 runs, the antimicrobial system in row has higher environmental impact than the system in column. Overall, the results indicate that the relative comparison of antimicrobial systems shown in Figure 4.6 largely are valid under the 1,000 Monte Carlo runs. More importantly, the three promising systems (i.e., WW+WW+SP, HW+WW+SP, PAA+WW+SP) remains among those with the lowest cost and environmental impacts. The impacts of choices between two different schemes of weighting for TRACI v2.1 are also investigated by illustrating the correlation relationship between SM weighting and equal weighting schemes as shown in SI, Figure S4.4. Strong linear correlations (R=0.99) for both scenarios all forty antimicrobial systems were found, suggesting that the two different
weighting schemes do not affect the environmental ranking of the forty antimicrobial systems.

The amount of devalued meat due to discoloration by hot water wash or steam pasteurization is crucial to the environmental and economic performance of the antimicrobial systems, as demonstrated in Figure 4.4 and Figure 4.5. Although the steam pasteurization and hot water wash have the potential to discolor the carcass and cause extra trimmings (Gill, 1999), the amount of trimmings induced by the thermal interventions remain uncertain between food processors. This is due to the complex practices and various customer requirements. In this study for comparison, we proposed two scenarios: 1) no devalued meat; 2) 0.1% of devalued meat based on onsite data collection and consultations with a group of experts from animal and meat science at the University of Nebraska-Lincoln. The bubble plot assuming no devalued meat from heat is provided in SI, Figure S4.3. A fixed reduction on the y-axis and x-axis can be observed for those antimicrobial systems that applying thermal treatment (i.e., hot water or steam), representing decreased environmental single score (1.75 mPt/1000 kg HSCW) and operational cost ($4.53/1000 kg HSWC) due to devalued meat. However, the three systems (i.e., WW+WW+SP, HW+WW+SP, PAA+WW+SP) in the scenario of 0.1% devalued meat remain superior to other systems even if no devalued meat occurs from thermal treatment.

Unlike Environmental Protection Agency’ National Primary Drinking Water Regulations that provide a degree of microbial removal and inactivation requirement (e.g., 99.9% removal/inactivation for Giardia Lamblia) (US EPA, 2018), there are currently no such regulations that provide a specific microbial load reduction requirement
for the antimicrobial systems within beef processing plants. However, the USDA Food Safety and Inspection Service has set zero tolerance for Shiga Toxin-Producing *Escherichia coli* organisms (i.e., E. coli O157, six non-O157 STECs) (USDA FSIS, 2019) and have considered them as adulterant in non-intact beef (e.g., ground beef, trimmings), thus the beef products cannot be sold if the samples are tested to be positive. If the plant maintains a high quality of hygiene controls and practices throughout the plant, this serves as a further preventative to microbial contamination.

**4.5 Conclusions**

This work serves as the first analysis at jointly evaluating effectiveness, environmental impacts, economic costs of antimicrobial systems of U.S. beef processing industry via an integrated life cycle assessment framework. Generally, if 4.5 log CFU/cm² reduction is desired, steam pasteurization as the main treatment is required. If only 4 log CFU/cm² reduction is preferred, hot water wash is viable without steam pasteurization. The best systems that include warm water wash or chemical acid spray without heat treatment cannot even achieve a 3.5 log CFU/cm² reduction. From the bubble plot (Figure 4.6 and Figure S3), two systems (i.e., HW+WW+SP, PAA+WW+SP) have microbial reduction greater than 4.8 log CFU/cm² with environmental impacts less than 3.5 mPt/1000 kg HSCW and operational costs less than $6/1000 kg HSCW even including devalued meat. The WW+WW+SP system has a slightly lower microbial load reduction (4.44 log CFU/cm²) but also offers better environmental and cost performance. The beef processors can apply the results from this study to decide the antimicrobial systems that work appropriately in their own cases. Ultimately, additional interventions
are encouraged to be compared with the forty antimicrobial systems evaluated in this study, as data becomes available. Other antimicrobial interventions considered promising include ionizing radiation, ozone (Mahapatra et al., 2005), and other different antimicrobial chemicals (e.g., acidified sodium chlorite and BoviBrom [1,3-Dibromo-5,5-dimethyl hydantoin]) (Kalchayanand et al., 2011). Electrostatic spraying can enhance the efficacy of uniformity of chemical application on the meats surface thereby reducing the use of chemicals which reduces costs and environmental footprints (Ganesh et al., 2010; Lyons et al., 2011; Vaze et al., 2018).

More data on the effectiveness of antimicrobial interventions especially applications of peracetic acid and other popular antimicrobial chemicals are needed to improve the quality of microbial load reduction estimates via systematic review and meta-analysis. The amount of devalued meat due to discoloration is crucial to the environmental and economic impacts of the antimicrobial systems and there is a knowledge gap on quantifying the actual devalued meat caused only by thermal pasteurization in interventions. Further investigation should involve commercial beef processing partners to examine the impacts of antimicrobial systems on the actual devalued meat. Food waste has been a crucial issue in many food-related industries, impacting the environmental sustainability and socio-economic development around the world. (Shafiee-Jood and Cai, 2016) Developers of antimicrobial systems should shape the research on given minimizing devalued meat caused by antimicrobial systems given that life cycle impacts of raising animals in the farm stage are dominant (Asem-Hiablie et al., 2019).
Regulations on antimicrobial chemicals should also be considered in the integrated framework for future research. For example, peracetic acid is widely used as an antimicrobial chemical during processing for the reduction of pathogens in the U.S. poultry and red meat processing industry (Bauermeister et al., 2008; King et al., 2005). However, peracetic acid-treated meat is not approved by European Food Safety Authority due to the needs for further assessment on environmental risks and resistance to antimicrobials (EFSA Panel on Biological Hazards (BIOHAZ), 2014). This export requirement by the European market is a significant factor in the movements of antimicrobial systems for U.S. beef processing industry and should be incorporated in the future work.
4.6 Appendix: Supporting information

4.6.1 Description of antimicrobial interventions investigated in this study

Table S4.1 Description of antimicrobial interventions investigated in this study

<table>
<thead>
<tr>
<th>Steps applied</th>
<th>Intervention name</th>
<th>Description</th>
<th>Abbreviation of intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-evisceration</td>
<td>Warm water wash</td>
<td>Warm water at 32 °C without chemicals</td>
<td>WW</td>
</tr>
<tr>
<td></td>
<td>Hot water wash</td>
<td>85 °C water wash</td>
<td>HW</td>
</tr>
<tr>
<td></td>
<td>Peracetic acid wash</td>
<td>Warm water at 32 °C with peracetic acid mixture (350 ppm)</td>
<td>PAA</td>
</tr>
<tr>
<td></td>
<td>Water wash followed by lactic acid spray</td>
<td>Warm water wash followed by lactic acid spray (4%) at 54 °C</td>
<td>WW-LA</td>
</tr>
<tr>
<td>Carcass wash</td>
<td>Water wash</td>
<td>Water wash at 32-38°C without chemicals</td>
<td>WW</td>
</tr>
<tr>
<td></td>
<td>Peracetic acid wash</td>
<td>Water wash at 32-38 °C with peracetic acid mixture (350 ppm)</td>
<td>PAA</td>
</tr>
<tr>
<td>Main treatment</td>
<td>Lactic acid spray</td>
<td>Lactic acid spray (4%) at 54 °C</td>
<td>LA</td>
</tr>
<tr>
<td></td>
<td>Steam pasteurization</td>
<td>Steam pasteurization at 100 °C</td>
<td>SP</td>
</tr>
<tr>
<td></td>
<td>Hot water wash</td>
<td>85 °C water wash</td>
<td>HW</td>
</tr>
<tr>
<td></td>
<td>Steam pasteurization followed by lactic acid spray</td>
<td>Steam pasteurization followed by lactic acid spray (4%) at 54 °C</td>
<td>SP-LA</td>
</tr>
<tr>
<td></td>
<td>Hot water wash followed by lactic acid spray</td>
<td>Hot water wash followed by lactic acid spray C (4%) at 54 °</td>
<td>HW-LA</td>
</tr>
</tbody>
</table>
4.6.2 Meta-regression equations applied in this study

Table S4.2 Meta-regression equations applied in this study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Water wash</th>
<th>Lactic acid spray</th>
<th>Peracetic acid wash (PAA)</th>
<th>Steam pasteurization</th>
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<td>$\beta_0$</td>
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<td>-0.27</td>
<td>-0.69</td>
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<td>$\beta_2$</td>
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<td>NS$^2$</td>
<td>NT$^3$</td>
<td>NT</td>
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<tr>
<td>$\beta_3$</td>
<td>0.013</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
</tbody>
</table>

Note:
1Parameters $\beta_0$, $\beta_1$, $\beta_2$, and $\beta_3$ are the regression intercept and slopes of IMC, Temp, and Time, respectively. E.g. the increased microbial reductions from hot water can be calculated for a water wash applied at 50°C as $50 \times 0.02$ or 1 log CFU/cm$^2$.
2Temperature and application time were found to be statistically not significant for lactic acid application and therefore not included.
3Temperature and application times could not be tested for PAA and SP due to data constraints, but would likely follow results seen in LA. As only the WW data from the meta-analysis showed a robust effect from application time and temperature.
### 4.6.3 Inventory data

Table S4.3 List of all 40 designs of antimicrobial systems investigated in this study

<table>
<thead>
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<th>Design ID</th>
<th>Design name</th>
<th>Design ID</th>
<th>Design name</th>
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<tr>
<td>1</td>
<td>WW+PAA+LA</td>
<td>21</td>
<td>WW-LA+PAA+LA</td>
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<tr>
<td>2</td>
<td>WW+PAA+SP</td>
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<td>3</td>
<td>WW+PAA+HW</td>
<td>23</td>
<td>WW-LA+PAA+HW</td>
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<tr>
<td>4</td>
<td>WW+PAA+SP-LA</td>
<td>24</td>
<td>WW-LA+PAA+SP-LA</td>
</tr>
<tr>
<td>5</td>
<td>WW+PAA+HW-LA</td>
<td>25</td>
<td>WW-LA+PAA+HW-LA</td>
</tr>
<tr>
<td>6</td>
<td>WW+WW+LA</td>
<td>26</td>
<td>WW-LA+WW+LA</td>
</tr>
<tr>
<td>7</td>
<td>WW+WW+SP</td>
<td>27</td>
<td>WW-LA+WW+SP</td>
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<td>8</td>
<td>WW+WW+HW</td>
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<td>WW-LA+WW+HW</td>
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<td>9</td>
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<td>WW+WW+HW-LA</td>
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<td>20</td>
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### Table S4.4 Foreground inventory data used in this study

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<tr>
<th>Steps</th>
<th>Intervention name</th>
<th>Natural gas MJ/tHSCW</th>
<th>Water L/tHSCW</th>
<th>Chemical g/tHSCW</th>
<th>BOD₅ loading g/BOD₅ tHSCW</th>
<th>Waste water equivalent*</th>
<th>Electricity L/tHSCW kWh/tHSCW</th>
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<tbody>
<tr>
<td>Pre-evisceration wash</td>
<td>Warm water wash</td>
<td>5.8</td>
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<td>Peracetic acid wash</td>
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<td>Peracetic acid wash</td>
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<td>Steam pasteurization</td>
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<td>Hot water wash followed by lactic acid spray</td>
<td>163.7</td>
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<td>1,607.3</td>
<td>1,327.3</td>
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</table>

Note:
* Wastewater equivalent was calculated as its BOD₅ loading (g BOD₅/tHSCW) divided by the BOD₅ loadings of 1 m³ overall slaughterhouse wastewater (1121 mg BOD₅/m³). tHSCW= 1000 kg hot standard carcass weight.
Table S4.5 Selected background processes from U.S.-EI 2.2 and Ecoinvent 3 databases (LTS, 2016; Wernet et al., 2016)

<table>
<thead>
<tr>
<th>Material or Process</th>
<th>Unit process description</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water supply</td>
<td>Tap water, at user/US- US-EI U</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>Natural gas, burned in boiler condensing modulating &gt;100kW/US- US-EI U</td>
<td>Processes for onsite resources consumption</td>
</tr>
<tr>
<td>Electricity</td>
<td>Electricity, at Grid, US, 2008 NREL/RNA U U</td>
<td></td>
</tr>
<tr>
<td>Lactic acid</td>
<td>Lactic acid {RER} production Alloc Def, U</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>Electricity, at Grid, US, 2008 NREL/RNA U U</td>
<td></td>
</tr>
<tr>
<td>Thermal energy</td>
<td>Natural gas, burned in boiler condensing modulating &gt;100kW/US- US-EI U</td>
<td></td>
</tr>
<tr>
<td>Chlorine</td>
<td>Chlorine, gaseous, lithium chloride electrolysis, at plant/GLO US-EI U</td>
<td></td>
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<td>Sodium hydroxide</td>
<td>Sodium hydroxide, 50% in H2O, production mix, at plant/US- US-EI U</td>
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<td>Biogas, flare</td>
<td>Refinery gas, burned in flare/GLO US-EI U</td>
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<tr>
<td>Fertilizer (avoided product)</td>
<td>Diammonium phosphate, as P2O5, at regional storehouse/US- US-EI U</td>
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<tr>
<td>Sodium hydrogen sulfide</td>
<td>Sodium hydrogen sulfite {RER} production Alloc Def, U</td>
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<td>Polyamines</td>
<td>Polyacrylamide {GLO} production Alloc Def, U</td>
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</tr>
<tr>
<td>Sludge, land applied</td>
<td>Sludge from pulp and paper production {RoW} treatment, landfarming Alloc Def, U</td>
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</tbody>
</table>

To quantify the actual lifecycle impacts of discolored meat, the environmental impacts for growing 1 kg beef meat from cradle to farm stage were obtained from a life cycle assessment study (Lupo et al., 2013) in U.S. Great Plains beef production systems (Table S6). The LCA study of beef meat on farm stage applied ReCiPe(Goedkoop et al., 2008) as the environmental life cycle impact assessment method and have some different environmental categories with TRACI v2.1 method. Therefore, we converted the original environmental categories from ReCiPe to be consistent with environmental categories from TRACI v2.1 method.
Table S4.6 Environmental impacts of 1 kg hot standard carcass weight (1 kg HSCW) on the farm stage

<table>
<thead>
<tr>
<th>Impact indicator</th>
<th>ReCiPe Indicator Unit</th>
<th>TRACI V2.1 Indicator Unit</th>
<th>Value in ReCiPe unit</th>
<th>Conversion factor</th>
<th>Value in TRACI unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq(^1)</td>
<td>kg CFC-11 eq</td>
<td>1.1E-07</td>
<td>1.0E+00</td>
<td>1.1E-07</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO(_2) eq</td>
<td>kg CO(_2) eq</td>
<td>2.7E+01</td>
<td>1.0E+00</td>
<td>2.7E+01</td>
</tr>
<tr>
<td>Smog</td>
<td>kg NMVOC(^2) eq</td>
<td>kg O(_3) eq</td>
<td>3.4E-02</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Acidification</td>
<td>kg SO(_2) eq</td>
<td>kg SO(_2) eq</td>
<td>3.1E-01</td>
<td>1.0E+00</td>
<td>3.1E-01</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>kg N eq</td>
<td>7.3E-02</td>
<td>1.0E+00</td>
<td>7.3E-02</td>
</tr>
<tr>
<td>Carcinogen</td>
<td>kg 1,4-DCB eq(^3)</td>
<td>CTU(_h)(^4)</td>
<td>9.2E-01</td>
<td>2.7E-07(^a)</td>
<td>2.5E-07</td>
</tr>
<tr>
<td>Non carcinogen</td>
<td>kg 1,4-DCB eq</td>
<td>CTU(_h)</td>
<td>9.2E-01</td>
<td>8.1E-08(^a)</td>
<td>7.5E-08</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>kg 1,4-DCB eq</td>
<td>CTU(_e)(^4)</td>
<td>2.7E-01</td>
<td>3.7E+00(^a)</td>
<td>9.9E-01</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM(_{10}) eq</td>
<td>kg PM(_{2.5}) eq</td>
<td>4.7E-02</td>
<td>7.5E-01</td>
<td>3.5E-02</td>
</tr>
<tr>
<td>Fossil fuel energy</td>
<td>kg oil eq</td>
<td>MJ surplus</td>
<td>1.1E+00</td>
<td>4.6E+01(^b)</td>
<td>5.0E+01</td>
</tr>
</tbody>
</table>

Note:
1. CFC-11 refers to Trichlorofluoromethane.
2. NMVOC refers to Non-methane volatile organic compounds.
3. 1,4-CDB refers to 1,4-Dichlorobenzene.
4. CTU\(_h\) = The comparative toxic unit for human toxicity impacts; CTU\(_e\) = The comparative toxic unit for aquatic ecotoxicity impacts.

\(^a\) Human health effect factor (cases/kg intake) and eco effect factor (PAF *m\(^3\)/kg emitted) were obtained from official USEtox 2.0 model and factors. (Rosenbaum et al., 2008)

\(^b\) Heating value of oil (45.5 MJ/kg) were obtained from the Engineering ToolBox. (Engineering ToolBox, 2008)
Table S4.7 Normalization value calculated and weighting coefficients of TRACI environmental impacts (Meijer, 2013; Ryberg et al., 2014)

<table>
<thead>
<tr>
<th>Category</th>
<th>Impact indicator</th>
<th>Normalization factor</th>
<th>Unit</th>
<th>Weighting coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecological damage</td>
<td>Acidification</td>
<td>90.9</td>
<td>kg SO(_2) eq/year/capita</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>Ecotoxicity</td>
<td>11000</td>
<td>CTU(_e) /year/capita</td>
<td>0.084</td>
</tr>
<tr>
<td></td>
<td>Eutrophication</td>
<td>21.6</td>
<td>kg N eq/year/capita</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>Global warming</td>
<td>24200</td>
<td>kg CO(_2) eq/year/capita</td>
<td>0.349</td>
</tr>
<tr>
<td></td>
<td>Ozone depletion</td>
<td>0.161</td>
<td>kg CFC-11 eq/year/capita</td>
<td>0.024</td>
</tr>
<tr>
<td>Human health damage</td>
<td>Carcinogen</td>
<td>0.0001</td>
<td>CTU(_h) /year/capita</td>
<td>0.096</td>
</tr>
<tr>
<td></td>
<td>Non-carcinogen</td>
<td>0.0011</td>
<td>CTU(_h) /year/capita</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Respiratory effects</td>
<td>24.3</td>
<td>kg PM(_{2.5}) eq/year/capita</td>
<td>0.108</td>
</tr>
<tr>
<td></td>
<td>Smog</td>
<td>1390</td>
<td>kg O(_3) eq/year/capita</td>
<td>0.048</td>
</tr>
<tr>
<td>Resource depletion</td>
<td>Fossil fuel depletion</td>
<td>17300</td>
<td>MJ surplus/year/capita</td>
<td>0.121</td>
</tr>
</tbody>
</table>

Table S4.8 Breakdown of cost in each intervention treatment

<table>
<thead>
<tr>
<th>Steps applied</th>
<th>Intervention name</th>
<th>Natural gas use</th>
<th>Water use</th>
<th>Antimicrobial chemicals</th>
<th>Waste water treatment</th>
<th>Electricity use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-evisceration</td>
<td>Warm water wash (WW)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.00</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Hot water wash (HW)</td>
<td>0.22</td>
<td>0.05</td>
<td>0.00</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Water wash followed by lactic acid spray (WW-LA)</td>
<td>0.03</td>
<td>0.06</td>
<td>1.86</td>
<td>0.17</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Peracetic acid wash (PAA)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.36</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Carcass wash</td>
<td>Peracetic acid wash (PAA)</td>
<td>0.11</td>
<td>0.27</td>
<td>2.14</td>
<td>0.34</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Water wash (WW)</td>
<td>0.10</td>
<td>0.19</td>
<td>0.00</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>Main treatment</td>
<td>Lactic acid spray (LA)</td>
<td>0.01</td>
<td>0.01</td>
<td>1.86</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Steam pasteurization (SP)</td>
<td>0.31</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Hot water wash (HW)</td>
<td>0.51</td>
<td>0.07</td>
<td>0.00</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Steam pasteurization followed by lactic acid spray (SP-LA)</td>
<td>0.32</td>
<td>0.01</td>
<td>1.86</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Hot water wash followed by lactic acid spray (HW-LA)</td>
<td>0.52</td>
<td>0.09</td>
<td>1.86</td>
<td>0.23</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Note: All units are in $/t HSCW. tHSCW = 1000 kg hot standard carcass weight
Figure S4.1 Univariate k-means clustering of overall log reductions for the 40 antimicrobial systems studied.
Figure S4.2 Pairwise comparison of 40 antimicrobial systems under Monte Carlo (MC) simulation (1,000 runs).

Figure 4.2 (A) shows the pairwise comparisons of environmental impacts while Figure 4.2 (B) compares economic cost. The arrow in the left represents that the antimicrobial systems are ordered based on their environmental and economic performance from low to high. A color gradient from white to red is used here to demonstrate the relative performance of pairwise antimicrobial systems under uncertainty. A pure red color in a cell means that among 100% of 1,000 MC runs, the antimicrobial system in row has higher environmental impacts than the system in column. Conversely, a pure white color means that among 1,000 MC runs, it cannot tell which system of the pairwise comparison is better than the other. In other words, each of the two pairwise systems has 500 runs than the other. As environmental impacts and economic cost are linearly correlated, a similar trend is also found in Figure (B).
Figure S4.3 Bubble plot of interactions among environmental impacts, operational costs (assuming no devalued meat occurred), and microbial log reductions for the 40 systems studied.

Note: HSCW, hot standard carcass weight. Each string of abbreviated name represents one antimicrobial system. For example, HW+WW+SP represents hot water wash in pre-evisceration wash, warm water wash in carcass wash, and steam pasteurization in main intervention. See the abbreviation of intervention and description in SI, Tables S4.1 and S4.3. Microbial log reduction (log CFU/m²) is 2.66-3.65 in Cluster 1, 3.85 to 4.44 in Cluster 2, and 4.82 to 5.10 in Cluster 3.
The weighting scheme has inherent subjectivity and is varying to different preferences that different stakeholders have for different environmental categories. We compared two weighting schemes 1) the SM weighting scheme that assigns unequal weight according to the significance of impacts; 2) an unweighting scheme that has equal weight to all TRACI v2.1 impact categories. The latter one is basically the summation of the normalized value across disaggregated impacts since it does not have any unequal coefficients. The correlation relationship between SM weighting and equal weighting schemes for two scenarios (i.e., no devalued meat and 0.1% devalued meat) are shown in Figure S5. Strong linear correlations suggest that the two different weighting schemes do not affect the environmental ranking of the forty antimicrobial systems in both scenarios.

Figure S4.4 Correlation plot of two weighting schemes applied to 40 antimicrobial systems under two assumptions of devalued meat. Note: HSCW= hot standard carcass weight.
Chapter 5

5. Comparing foodborne, environmental and occupational human health impacts from the U.S. beef slaughtering and consumption

5.1 Abstract

Foodborne pathogens and occupational hazards are two primary safety concerns for U.S. beef slaughterhouses. The anthropogenic environmental impacts due to intensive resource use and pollution also exert threats to human health. Quantifying human health impacts from various sources remain a grand sustainability challenge for U.S. beef industry. We develop a framework to systematically estimate and compare human health impacts associated with U.S. beef foodborne illnesses from major pathogens and environmental impacts and occupational hazards from U.S. beef slaughtering on a common metric, disability-adjusted life year (DALY). Foodborne illnesses and occupational hazards are estimated by synthesizing published data and methodologies while environmental impacts are quantified using life cycle assessment. In spite of inherent uncertainties in estimation, results show that the environmental impacts and occupational hazards from beef slaughtering are of same magnitude with foodborne illnesses from beef consumption on human health. *Salmonella* and *Clostridium perfringens* contribute 51% and 28%, respectively, to the beef foodborne DALY; Global
warming and fine particulate matter formation, due to electricity and natural gas use, are primary drivers for environmental DALY, accounting 62% and 28%, respectively. Occupational DALY is on average lower than environmental DALY from beef slaughtering and foodborne DALY. The impact of new food safety interventions that use additional resources to improve food safety should be considered jointly with environmental impacts and occupational hazards to avoid unintended shifts and net increase of human health impacts. The methodology and results from this study provide a new perspective on reforms of the U.S. food safety regulations building toward sustainability in the food processing industry.

5.2 Introduction

Centers for Disease Control and Prevention (CDC) estimated that about 639,640 illnesses, 3,075 hospitalizations, and 55 deaths caused by foodborne diseases in the U.S. annually are attributed to beef using foodborne outbreaks data between 1998 and 2008 (Painter et al., 2013). Disability-adjusted life years (DALY) is a metric proposed by the World Health Organization (WHO) to account overall disease burden associated with health problems, including years of life lost (YLL) due to mortality and years lost due to disability (YLD), with one DALY representing the loss of one healthy year (Murray and Lopez, 1996). The beef slaughtering stage has been a primary focus of food safety interventions. In a surveillance report from CDC for foodborne diseases outbreaks in the U.S. between 2009 and 2010, beef was the food that accounted the most foodborne outbreaks that connected food with ingredients from one of the seventeen predefined food commodities (CDC, 2013; Painter et al., 2013). Havelaar et al. investigated disease
burden of foodborne diseases caused by fourteen leading pathogens using DALY and showed that beef disease burden ranking at the third largest contributor followed by pork and poultry in the Netherlands in 2009 (Havelaar et al., 2012).

One key step in preventing beef foodborne diseases through the beef supply chain lies in the slaughtering stage where various antimicrobial interventions are applied to minimize pathogenic contamination to the meat from beef hides and guts (Elder et al., 2000; Gansheroff and O’Brien, 2000). The U.S. Department of Agriculture (USDA) has enforced Hazard Analysis and Critical Control Points (HACCP) program to reduce the risk of foodborne outbreaks due to the insufficient food safety interventions and inappropriate sanitation practices (USDA FSIS, 1996). However, minimizing pathogenic contamination on beef products within slaughterhouses is at the expense of consuming intensive resources (water, energy, chemicals, etc.) (Hansen et al., 2000), producing high strength wastewater (Bustillo-Lecompte and Mehrvar, 2015) and solid waste (Peters et al., 2010) and posing occupational threats on workers safety (US Government Accountability Office, 2005). The illness and injury rates (i.e., cases per 100 full-time workers) for the meat industry are higher than that for other U.S. private industries (e.g., manufacturing, construction, retail trade), due to the exposure to dangerous machinery, toxic chemicals, greasy floors, pathogenic hazards, etc. (Bureau of Labor Statistics, 2016; Occupational Safety and Health Administration, 2017). Due to differences in the metrics, however, data of occupational injuries from BLS cannot be directly compared with other foodborne and environmental human health impacts.

The disease burden expressed in DALY has been adopted to evaluate impacts on human health in various industry (Dhondt et al., 2013; Dong et al., 2016; Heimersson et
Environmental impacts on human health can be evaluated using life cycle assessment (LCA), an international standardized method (ISO14040-14044) for quantifying environmental impacts of products or systems from raw materials extraction, manufacturing, operation, and to its end of life (Jolliet et al., 2018). LCA has been widely applied in food production systems to assess their sustainability (Henriksson et al., 2018). However, there has not been detailed process-level LCA study for U.S. beef slaughtering industry. Heimersson et al. (2014) include pathogen risk with life cycle assessment to compare pathogen impacts with other environmental impacts on human health and have found pathogen risks can contribute up to 20% of total human health impacts from combined environmental and pathogenic risks in municipal wastewater treatment systems. Scanlon et al. introduce a methodology of integrating occupational hazards into account of life cycle assessment and demonstrate it in municipal solid waste treatment systems (Scanlon et al., 2015). The results show that occupational hazards contribute to 20% and 12% of total combined DALY from environmental and occupational health risks based on landfill and incineration, respectively. Those studies show the necessity and feasibility of evaluating human health impact from various sources in our society. However, none of studies have investigated foodborne pathogen, environmental, and occupational impacts on human health together.

As global meat consumption is expected to increase and the U.S. beef is expected to play an important role of global meat supply chain (Charles et al., 2018), advancing the sustainability of U.S. beef slaughtering is an important need. The overarching research question addressed is: What is the relative importance of the three impacts (i.e. beef foodborne illness, environmental impacts and occupational hazards from beef
slaughtering) on human health? Most assessments of those impacts on human health are studied separately and do not offer a comprehensive view to fully understand the overall human health impact. Such comprehensive assessment is especially important for the beef industry that currently focuses on effectiveness of food safety interventions but not as much on the environmental impacts on human health. With increasing consumers’ interest in sustainable beef, a simultaneous assessment of all impacts is gaining interests. The overarching objective of this work is to develop a framework (described schematically in Figure 5.1) for comparing disease burden expressed in DALY caused by foodborne illnesses from U.S. beef consumption, and environmental impacts and occupational hazards from U.S. beef slaughtering.

5.3 Methodology

The schematic overview of the methodology for calculating these three sources of disease burden expressed in DALY were illustrated in Figure 5.1. The left panel introduces three impacts on human health: foodborne illnesses, environmental impacts, and occupational hazards. The middle panel presents methods applied to calculate the three impacts individually. The right panel shows human health outcome expressed in DALY. The concept of disability-adjusted life years (DALY) proposed by the WHO is used to compare human health impacts in this study. More details regarding DALY can be found in the original work (Murray and Lopez, 1996). For calculating disease burden of foodborne illnesses and environmental impacts, we apply characterization-based method to estimate their disease burden. Specifically, the DALY per foodborne illness caused by various pathogens was estimated from literature and then applied to beef
Foodborne illness. The characterization factors of environmental impacts (e.g., DALY per kg pollutant emitted via different compartments) are obtained from well-establish impact assessment method such as ReCiPe 2016 (Huijbregts et al., 2017) and USEtox 2.0 (Marian Bijster et al., 2017). For occupational hazards, DALY is calculated combining years of life lost (YLL) and years lived with disability (YLD). Details regarding on calculating the three sources of disease burden are described below.

Figure 5.1 Schematic view of the framework for determining disability-adjusted life year (DALY). Note: BLS = Bureau of Labor Statistics.
5.3.1 Disease burden of foodborne illnesses from beef consumption

5.3.1.1. Attribution of foodborne illnesses caused by seven major pathogens

Disease burden of foodborne illnesses from beef consumption was estimated by combining findings from published studies on foodborne diseases. Annual foodborne illnesses related to beef consumption were retrieved from the findings of Painter et al. (2013) as shown in the Supplementary Information (SI) Appendix, Table S5.1. In Painter et al. (2013), all foodborne outbreaks reported to the CDC from 1998 to 2008 were reviewed and total annual US foodborne illnesses were attributed to 17 food commodities caused by 31 major pathogens (Scallan et al., 2011b). Nine pathogens among 31 major pathogens were linked to foodborne illnesses with beef and about 94% of foodborne illnesses related to beef was contributed by those seven leading foodborne pathogens (SI Appendix, Table S5.1).

5.3.1.2. Attribution of DALY per 1000 foodborne illnesses

DALY per 1000 cases of illnesses of each pathogen were calculated based on two studies evaluating human health foodborne impacts expressed in DALY. In this study, the characterization factor (i.e. DALY per 1000 cases) of seven major pathogens, accounting 94% of the nine pathogens, were available in the literature and thus considered in this study. Data on five pathogens (DALY per 1000 foodborne cases) were retrieved from the study focusing on the United States (Scallan et al., 2015a), including \textit{Clostridium perfringens}, \textit{E. coli O157}, \textit{Listeria monocytogenes}, \textit{Norovirus}, \textit{Salmonella}. The DALY data of other two remaining pathogens were \textit{Bacillus cereus} and \textit{Staphylococcus aureus}, obtained from the study focusing on Netherland (Havelaar et al., 2012).
The total YLD from the seven leading pathogens were determined including acute illnesses (e.g., acute gastroenteritis) and sequelae (e.g., Guillain–Barré syndrome, reactive arthritis, post-infectious irritable bowel syndrome). The total YLL from the seven leading pathogens was calculated by multiplying number of deaths by remaining longevity at the time when death occurred. Calculating such YLD and YLL requires multiple data sources. More detailed information regarding methods and data sources can be found in the work of Scallan et al. (2015) The total YLD and YLL caused by the seven leading pathogens were then divided by the foodborne illnesses caused by each pathogen and normalized to 1000 foodborne illnesses, resulting in the unit of DALY/1000 foodborne illnesses (SI Appendix, Table S5.2). The number of foodborne illnesses were multiplied by the DALY/1000 illnesses to obtain the annual estimated DALY (SI Appendix, Table S5.3).

5.3.2 Disease burden of environmental risks from beef slaughtering

5.3.2.1 Scope and system description

The environmental impacts on human health from beef slaughtering were estimated using LCA in SimaPro 8.4 LCA software (PRé Consultants, The Netherlands). The system boundary of the studied beef slaughterhouse consists of on-site resource usage (e.g. consumption of water, electricity, natural gas, wastewater treatment, chemical and packaging materilas, solid waste generation). The environmental impacts account for downstream impacts such as solid waste transport and disposal and wastewater treatment, and those from upstream activities such as extraction and production of energy, chemicals, packaging and other materials. The term “slaughtering” used in this study includes the entire process flow diagram starting from receiving cattle until producing
boxed beef cuts ready for shipping to retailers (Figure 5.2). Cattle are delivered to the pen yard and driven to the kill floor where a series of slaughtering activities take place, including stunning, bleeding and blood separation, hide and head removal, evisceration, antimicrobial treatments, etc. The split carcasses are then sent to chilling room for 24-48 hours before fabricating. In the fabrication floor, the spit carcasses are cut and deboned into primal cuts, such as chuck, rib, loin, etc. After fabrication, the beef products are packaged and stored under refrigeration.

Figure 5.2 System boundary of the U.S. beef slaughtering in this study

5.3.2.2. Life cycle inventory

Inventory data on detailed process level were primarily obtained from two typical commercial beef slaughterhouses located in the Midwest of U.S., including all water, electricity, natural gas, packaging materials, chemical usage, solid waste (i.e. plastics,
organic waste), and wastewater treatment associated with the beef slaughter process from within the plant’s system boundaries. The energy consumption in beef slaughterhouse includes operational electricity use for refrigeration and equipment and thermal energy for steam production. The energy from equipment installation, such as refrigeration installations, is not considered in this study due to data limitation and energy of installation is assumed to be negligible compared to operational energy over 20 years life span (Morera et al., 2017). The chemicals applied in beef slaughterhouse are used for cleaning, antimicrobial treatment, general processing, oils and lubricants. Environmental impacts of wastewater water treatment include onsite resources (e.g., energy, chemicals) in an industrial wastewater treatment plant specifically for treating slaughterhouse wastewater and the water quality of the effluent (Li et al., 2018a). The waterborne emissions of active ingredients of chemicals enter the wastewater plant for treatment. Inventory data were collected using a combination of methods, including onsite measurement, vendors’ invoices, plant’s utility bills and plant’s discharge reports over two years (Li et al., 2018b, 2018a; Ziara et al., 2018). Detailed inventory data are provided in SI Appendix, Table S5.4.

Background database on the production of these resources and treatment of solid wastes are provided in SI Appendix, Table S5.5. Background database was obtained from US-EI 2.2 database (LTS, 2016), a database that replaces Europe data with U.S. data in the ecoinvent database v3.3 (Wernet et al., 2016) wherever U.S. data are available. Specific processes data of rendering process and manure disposal and management are listed in SI Appendix, Tables S5.6 and S5.7, respectively. As this work focused on resource inputs and waste outputs during beef slaughtering, economic outputs of products
(e.g., meat) and by-products (e.g., blood, bone, viscera) from beef slaughterhouse are not considered in this study.

5.3.2.3. **Life cycle impact assessment**

A variety of environmental impact connected with environmental resources consumption and emissions can make damage to human health through various midpoint indicators, including global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, particular matter formation, human toxicity (i.e., cancer and non-cancer toxicity), water consumption (Huijbregts et al., 2017). These midpoint indicators exert threats to human health via various damage pathways, including respiratory disease, different types of cancers, other diseases, and malnutrition. The characterization-based methods for these environmental impacts were adopted from the ReCiPe 2016 to calculate the endpoint impact (i.e., human health) expressed in DALY (Huijbregts et al., 2017). It is recognized that the ReCiPe method developed in Europe may not be as relevant to the United States as other assessment method, such as TRACI developed by U.S. EPA (Bare, 2012). However, the ReCiPe method converts environmental midpoint indicators to the endpoint human health impact in DALY, allowing comparisons of various sources of disease burden in the same context, which has been applied in other studies to evaluate human health tradeoffs of various systems. Internationally accepted methodologies are available for converting most midpoint indicators from ReCiPe 2016 into the end point on human health. However, characterization factors of human toxicity are still under development. To comprehensively quantify toxicity impacts on human health, we applied both models (ReCiPe 2016 and USEtox 2.0) for comparison (Huijbregts et al., 2017; Marian Bijster et al., 2017). The health impacts from odors and
noise during beef slaughtering activities cannot be quantified using current available assessment methods (i.e., ReCiPe 2016). However, the health impacts from odors and noise may be reflected in the occupational hazards when associated injuries are reported to the Injuries, Illnesses, and Fatalities (IIF) program.

5.3.3 Disease burden of occupational risks from beef slaughtering

Occupational hazards to human health have not been incorporated into the existing life cycle impact assessment methods (e.g., TRACI v2.1 and ReCiPe 2016). Scanlon et al. (2013) developed the methodology named work environment disability-adjusted life year (WE-DALY) to estimate disease burden of occupational hazards, expressed in DALY. WE-DALY utilized data on industry-wide work-related injuries, illnesses, and fatalities reported by BLS to quantify hazards in DALY associated with worker safety from various hazards, such as physical, chemical and biological hazards. WE-DALY is composed of YLL and YLD based on industry-wide fatal and nonfatal injuries data from the U.S. Census Bureau North American Industrial Classification System (NAICS) code (US Census Bureau, 2012).

Three NAICS codes are relevant to occupational hazards in beef slaughtering and were extracted from BLS, including 1) NAICS 311611 “Animal (except poultry) slaughtering”; 2) NAICS 311612 “Meat processed from carcasses”; and 3) NAICS 56172 “Janitorial services”. Specifically, NAICS 311611 and NAICS 311612 were related to production activities in beef slaughtering while NAICS 56172 was connected with cleaning and sanitation activities in beef slaughterhouses based on the number of employees. Those NAICS codes do not specifically represent the beef industry. Therefore, two methods were applied to allocate DALY of those NAICS codes. For
NAICS 3116111 and 311612, we allocated DALY to beef meat based on the fraction of the weight of beef meat to the total weight of various meat. We include NAICS 311612 to fully consider the meat processed in the slaughterhouse, although we recognize that NAICS 311612 also includes other meat processing facilities that do not slaughter. For NAICS 56172, we allocated DALY to beef industry based on the ratio of the numbers of janitorial workers in beef slaughtering plants to the total numbers of janitorial workers across all industry. The allocation methods are provided in SI Appendix, Tables S3.26 and S3.27. Details regarding the procedures and calculations YLD and YLL for the three NAICS codes are provided in Part 3 of SI Appendix, Tables S5.12 to S5.25. A summary of DALY from occupational hazards related to the U.S. beef slaughtering industry is provided in Table S5.29.

5.3.4 Normalization reference

The disease burden (DALY) was calculated using the same normalization reference value, as 1000 kg live-weight beef (1000 kg LW beef). The carcass weight was converted to live weight equivalent for foodborne illnesses calculation (USDA ERS, 2018a) based on the average annual U.S. domestic beef consumption between 1998 to 2008 since the time period (1998-2008) is consistent with the foodborne data. The total annual cattle in live weight in the U.S. was used for normalizing environmental impacts and occupational hazards from U.S. beef slaughtering (USDA ERS, 2016). Due to exports and imports of beef, the U.S. beef slaughtering and U.S. beef consumption have two slightly different system boundaries. The amount of beef consumed and processed in the U.S. are assumed to be same due to the almost equivalent mass of U.S. beef imported
and exported, both accounting about 7 to 10% of the U.S. beef market (USDA ERS, 2016).

5.3.5 Uncertainty estimates

For DALY estimation on foodborne illnesses, this study captured uncertainty regarding the range of the numbers of foodborne illnesses for each specific pathogen. That is minimum, most probable, and maximum numbers of foodborne illnesses extracted from original data on the literature (Painter et al., 2013). Uncertainty associated with DALY per 1000 cases for each pathogen was not presented due to insufficient data available to derive appropriate distributions. For DALY estimation on environmental impact, uncertainty underlying in background processes and on-site inventory data was estimated by a Monte Carlo Analysis (1000 runs) within SimaPro 8.4 LCA software (PRé Consultants, The Netherlands). Frequency distributions on background process were provided by their databases while frequency distributions of onsite inventory data were evaluated by Pedigree matrix built within SimaPro 8.4 (Ciroth et al., 2016).

Underestimation of work-related injuries and illnesses has been a major issue in the BLS data (Leigh et al., 2004). For DALY estimation on occupational hazards, uncertainty due to undercounting issues of nonfatal injuries reported from U.S. BLS was assumed as 50% in this study, based on undercount estimates from the public literature that reported an underestimation between 33% and 69% of nonfatal injuries (Leigh et al., 2004). The uncertainty of other factors related to occupational DALY estimation (e.g., disability weight, duration time, attribution of short-term and long-term injuries) was not evaluated in this study due to data limitations.
5.4 Results and discussion

Figure 5.3 presents the disease burden by seven primary pathogens on a general-consumer level (DALY per 1000 kg LW beef) and an infected-consumer level (DALY per 1000 cases) based on data from the literature on the national scale (Havelaar et al., 2012; Painter et al., 2013; Scallan et al., 2015a). Tails represent minimum and maximum estimates of DALY per 1000 kg live-weight beef while markers represent most probable estimates. Note horizontal axis is on a logarithmic scale. *Salmonella* results in the highest disease burden for the general consumer.

Figure 5.3 Ranking of disability-adjusted life year (DALY) caused from seven primary pathogens normalized by beef weight (y-axis) and by the number of cases (x-axis).

*Escherichia coli* O157 cause a similar number of infected consumers as *Salmonella*, but the disease burden for general consumers is only around one-fifth of that from *Salmonella* due to less severe symptoms. *Listeria monocytogenes* causes the highest disease burden per case but has a lower DALY per 1000 kg LW beef due to the lower number of cases. *Clostridium perfringens* has a relatively mild burden per case but the
burden for general beef consumers is ranked as a second place due to the higher frequency of cases. Norovirus, *Bacillus cereus*, and *Staphylococcus aureus* cause a lower burden for both general and infected consumer. There is a significant variability of the burden on the general-consumer level from *Salmonella* and *Listeria monocytogenes* due to the uncertainty of the estimated number of cases.

As shown in Figure 5.4A, global warming and fine particle matter formation were found to be the two dominant environmental categories for human health impacts, accounting 62% and 28% of total environmental DALY, respectively, as illustrated by the breakdown of total environmental DALY. Human toxicity (6%) and water consumption (4%) have fewer impacts on the overall human health while human health impacts from the other environmental pollutants (i.e., ozone formation, stratospheric ozone depletion, and ionizing radiation) are relatively minimal (0.4%). From resources perspective, the onsite consumption of natural gas and electricity for slaughtering cattle at plants are the two major contributors, responsible for 34% and 32%, respectively. This is mainly due to their carbon dioxide and sulfur dioxide emissions, thus causing human health impacts through global warming and fine particulate matter formation. The rendering process contributes about 11% of total environmental DALY, since the rendering process is also an energy intensive process where bones, fats, meat scraps were rendered into a wide range of byproducts (e.g., edible lards, bone meal). Full process contribution can be found in SI Appendix, Table S5.8.
Figure 5.4 Disability-adjusted life year (DALY) by various environmental midpoint categories from beef slaughtering: (A) Breakdown of environmental impacts using ReCiPe method. (B) Comparison of human toxicity result from two methods (i.e., ReCiPe 2016 and USEtox 2.0).

The human toxicity using characterization factors from USEtox 2.0 is about 5-fold higher for human toxicity than the ReCiPe 2016 method shown in Figure 5.4B. Most sources result in a higher human toxicity using the USEtox 2.0 method, with the sludge from wastewater treatment being the largest due to heavy metal emissions. The main heavy metals contributing to human toxicity are substances Zinc, Chromium VI and Mercury. Detailed substance contribution is provided in SI Appendix, Tables S5.9 to S5.10. The contribution to the difference between the two methods are also quantified in SI, Appendix Table S5.11 with Zinc contributing (21%), Chromium VI (23%) and
Mercury (10%). Similar differences are found in other studies (Heimersson et al., 2014; Rosenbaum et al., 2008). The ReCiPe 2016 method uses a global multi-media fate, exposure, and effects model named “USES-LCA 2.0” to evaluate the cancer and non-cancer toxicity on human health (van Zelm et al., 2009) while USEtox 2.0 was developed based on several models, including USES-LCA (Rosenbaum et al., 2008). For consistency, we use human toxicity results based on ReCiPe 2016 to compare with the other two impacts in the subsequent comparison (Figure 5.6). The uncertainty bar of environmental impacts stands for lower and upper bounds at 95% confidence intervals via Monte Carlo simulation (1,000 runs). Total chemicals include chemicals used during processing and cleaning, and other uses (e.g., oils and lubricants).

Beef slaughtering not only consumes resources and produces wastes, but also causes higher injury rates than the average across U.S. private industries (Occupational Safety and Health Administration, 2017). Figure 5.5 quantifies occupational hazards in DALY, allowing a comparison to environmental and foodborne human health. Soreness, sprains, strains, tears, cuts, lacerations, bruises, and punctures, are combined as “Others”. A large number of occupational injuries have been reported to Injuries, Illnesses, and Fatalities (IIF) program as unspecified nonfatal injuries, thus unable to be classified into the specific codes based on Occupational Injury and Illness Classification System (Bureau of Labor Statistics, 2012) (SI Appendix, Table S3.1). As illustrated in SI Appendix, Tables S3.3 and S3.6, duration assignment and he disability weights of unspecified injuries were averaged from the other specific injuries provided by IIF. It was found that unspecified nonfatal injuries have the highest occupational disease burden (39%). Multiple traumatic injuries involve traumatic disorders with equal severity is
responsible for 22% of the entire occupational human health impacts, followed by amputations (14%), fatal injuries (11%), carpal tunnel syndrome (8%), and the combination of heat and chemical burns (6%). It is noted that human toxicity does not explicitly include impact of chemical toxicity on the employees at workplace of the beef processing plants. Instead, it would be included as the occupational hazards if employees experience notable injuries due to the exposure to chemical toxicity and injuries are reported.

Figure 5.5 Disability-adjusted life year (DALY) caused by various occupational hazards during beef slaughtering.

Most DALY caused by occupational hazards is connected to life-long nonfatal injuries as shown in Figure 5.5. The duration of lifelong injuries is usually two to three orders of magnitude higher than the duration of short-term injuries (SI Appendix, Table S3.5), thus lifelong injuries being a major contribution of occupational DALY. Similar findings are also found in other studies quantifying public health impact. For example, in a study evaluating drinking water on public health impacts, long-term diseases have
controlling effects on human health impacts using DALY (Havelaar and Melse, 2003). Most lifelong injuries occur during processing shift of beef slaughterhouses, where a large number of workers, are engaged in activities such as slaughtering, cutting, and fabricating.

Figure 5.6 compares the relative human health impacts from foodborne illnesses from beef consumption, environmental impacts and occupational hazards from beef slaughtering. The uncertainty bar of foodborne illnesses represents disability-adjusted life year (DALY) caused by the minimal and maximum cases of foodborne illnesses. The uncertainty bar of environmental impacts stands for lower and upper bounds at 95% confidence intervals via Monte Carlo simulation 1,000 random samplings. The uncertainty bar of occupational hazards assumes 50% of unfatal injuries are not reported. The foodborne illnesses are separated by pathogen. The total environmental impacts are displayed from two perspectives: 1) by midpoint (e.g., global warming, particulate matter formation) and 2) by process to which resource uses are allocated. Different types of injuries separate the occupational hazards. The stacked bar of environmental impacts by process was further separated into two groups (i.e., directly relevant to food safety and indirectly relevant to food safety) to better understand the contribution of environmental impacts from various processes at plant to the total human health impacts (Figure 5.6). The following six processes as directly relevant to food safety are: 1) natural gas for water heating for sanitation; 2) electricity for cooling; 3) packaging materials; 4) chemicals (processing shift); 5) chemicals (cleaning shift); 6) onsite water use, accounting 42% of the entire environmental human health impacts. The other 58% are considered as not directly related to food safety (e.g., wastewater treatment, electricity for
processing equipment, natural gas for space heating), but may be impacted by food safety changes (e.g., use of larger organic acid flow rates may increase resources required for wastewater treatment).

The foodborne illnesses are responsible for $2.4 \times 10^{-4}$ DALY (minimum: $1.2 \times 10^{-4}$ DALY; maximum: $6.0 \times 10^{-4}$ DALY) per 1000 kg LW beef. The environmental impacts from beef slaughtering cause $3.6 \times 10^{-4}$ DALY ($2.3 \times 10^{-4}$ to $5.0 \times 10^{-4}$ DALY at 95% confidence interval) per 1000 kg LW beef. The occupational hazards connected to beef slaughtering cause $6.6 \times 10^{-5}$ DALY for processing 1000 kg live weight if all injuries are reported to IIF and $1.2 \times 10^{-4}$ DALY if only 50% of nonfatal injuries are reported to IIF. Quantifying disease burden from various sources involves assumptions due to inherent heterogeneity and lack of information and knowledge on specific diseases. A general conclusion could be that disease burden expressed in DALY from the three impacts are comparable to each other considering the uncertainty. DALY from occupational hazards is lower than foodborne and environmental DALY even though 50% of underreporting of nonfatal injuries was assumed.

This study presents an integrated framework for evaluating human health associated with U.S. beef consumption and slaughtering. The overall goal of this work is to help decision makers target efforts on controlling and minimizing the overall human health impacts related to the U.S. beef consumption and slaughtering. Such a comparable assessment enables the evidence-based discussion about policy and initiatives of the beef industry. Further examination should be performed for some relatively resource-intensive steps at slaughtering plants to optimize the overall public health DALY reductions. As environmental impacts and foodborne illnesses are negatively correlated, any
Improvements in food safety interventions should be compared with the sum of the two impacts for baseline scenario. Currently available LCA methods do not include characterization factors of two important human health concerns (i.e., foodborne illness and occupational hazards). The results from this study can serve as new characterization factors for beef products in future LCA studies.

Figure 5.6 Comparison of the three impacts on human health.
The resources used in beef slaughterhouses (e.g., electricity for cooling and packaging materials) are used for preventing beef products from being spoiled, thus reducing significant amount of food waste and its related environmental impacts. Such an essential and beneficial function of resources have not been reflected in the DALY estimated in this study. Optimizing resource use efficiency may focus on processes not directly contributing to improving food safety but causing high environmental human health impacts, such as electricity for processing (i.e., equipment motors and lighting systems) and natural gas for space heating.

Foodborne illnesses caused by unspecified agents have not been included due to insufficient data and understanding to attribute sources to beef consumption (Scallan et al., 2011a). In this study, seven leading pathogens representing 94% of total foodborne cases due to beef consumption in the U.S. were investigated. In this respect, the contribution of foodborne DALY may increase if impacts from unspecified pathogens are considered. It is also recognized that not all beef foodborne diseases are caused by insufficient sanitation at the stage of beef slaughtering plants. It could be caused by improper cooking and cross-contamination at the consumer stage. However, a research gap still exists on how to track the sources causing beef foodborne diseases back to beef consumption or slaughtering stages. Obradovich et al. (2018) employed millions of data points from regulatory agencies to track the impacts of temperature and precipitation on daily activities of regulators (Obradovich et al., 2018). More transparent and granular data are needed for the industry and researchers to track foodborne illness data with environmental impacts and occupational hazards associated with food safety interventions during processing through the big data analysis such as the study of
Obradovich et al. (Obradovich et al., 2018) or through open and distributed data system (e.g., blockchain) (Yiannas, 2018).

It has been reported that around $2 \times 10^{-2}$ to $3.0 \times 10^{-2}$ DALY is associated with environmental life cycle impacts for treating 10,000 m$^3$ of wastewater (Heimersson et al., 2014). In our study, the environmental life cycle impacts at the beef slaughtering are about $3.6 \times 10^{-4}$ DALY per 1000 kg LW beef, which is comparable to human health burdens caused by treating 100 m$^3$ wastewater, which is slightly less than the annual wastewater per capita in the United States (USGS, 2016). The combined disease burden from the three impacts is $6.6 \times 10^{-4}$ DALY per 1000 kg LW (Figure 5.6), which is equivalent to about 20.1 minutes loss of healthy life based on the per capita U.S. beef consumption of 35.9 kg in carcass weight annually in 2016 (USDA ERS, 2018).

Key strategies within the beef slaughtering to reduce environmental impacts include 1) optimizing electricity, natural gas, and chemicals within processes, 2) utilizing cleaner sources for electricity production, 3) decreasing direct emissions of carbon dioxide, sulfur dioxide, and methane from natural gas combustion via boiler, 4) reducing onsite cold and hot water consumption concurrent with burdens from wastewater treatment, and 5) developing and adopting greener packaging materials and chemicals that impose less burdens to the environment. As natural gas and electricity consumption are the two major contributors to the human health impacts by environmental pollutions, upgrading cleaner energy sources and optimizing efficiency of energy use at plant may offer the largest human health benefits. Environmental impacts caused by beef slaughtering may be dwarfed when comparing to that in beef pre-harvest stage (i.e., feed, cow-calf, and feedlot) due to the nature of cattle growth that produces large amount of
methane as a greenhouse gas and requires intensive energy and water (Battagliese et al., 2015; Eshel et al., 2014). However, resources and pollutions from pre-harvest stage are related to beef growth rather than beef safety and thus is excluded from this discussion.

Scanlon et al. (2015) applied the occupational approach as applied in this study and concluded $1.3 \times 10^{-7}$ DALY and $2.6 \times 10^{-7}$ DALY are associated with treating one kilogram of municipal solid waste by incineration and landfill, respectively. In other words, the occupational hazards from beef slaughtering ($6.6 \times 10^{-5}$ DALY per 1000 kg LW beef) are equivalent to occupational hazards for disposing of 254 to 508 kg of municipal solid wastes. Reduction of occupational hazards is anticipated to be largely independent of the food safety steps, since a key to the reduction may be improvements in training programs for personal protective equipment and replacing manual-control equipment with automated equipment. Reductions of antimicrobial chemical and energy uses may also reduce the hazards of chemical and heat burns, and other concurrently traumatic disorders.

As identified in Figure 5.6, 42% ($1.5 \times 10^{-4}$ DALY/1000 kg LW) of the entire environmental human health impacts at plant are associated with food safety steps. For occupational hazards, injuries due to heat and chemicals burns are identified to be relevant to food safety operations, accounting about $3.6 \times 10^{-6}$ DALY/1000 kg LW. These two combined impacts (i.e., environmental impacts and occupational hazards) from food safety steps at plant is on average lower than foodborne illnesses ($2.4 \times 10^{-4}$ DALY). New or modified food safety interventions should be considered jointly with environmental and occupational impacts to prevent unintended shifts or increases in human health impact. Careful application of additional resources to food safety
interventions may reduce foodborne DALY, with minimal increase in environmental and occupational impacts. The results from this study can serve as a baseline for evaluating incremental human health benefits from various interventions.

Like other studies on human health assessments, our work has several limitations even though based on the best data currently accessible. Data on the three impacts were obtained from the different time periods and thus human health damages might be slightly different. In addition, certain specific processes (e.g., blood separation and treatment, different types of solid waste) are aggregated into more general processes (e.g., general solid waste for landfill). An exhaustive LCA is needed to enhance the standings environmental impacts on human health from specific processes. However, collecting the detailed process-level data in commercial beef facilities are challenging in many aspects, which took two years to finish the data collection. The two plants are considered as typical slaughterhouses as they apply typical processes and their overall resource uses (e.g., water, energy) are in the range of reported values in the literature (Li et al., 2018b). Therefore, we believe that gathering additional data on resource usage of additional specific processes will not change the overall conclusions of this work. Occupational hazards of beef slaughtering facilities during the construction stage were not considered in this study due to data limitations. Construction of facilities and infrastructure equipment can contribute considerable occupational DALY compared to the operating stage (Scanlon et al., 2015).

Although there is uncertainty inherent with human health studies, the framework used in this study has broad implications for the other food processing industry. Future study should continue comparing the human health impacts from other food processing
sectors (e.g., pork, poultry, dairy, egg) on the same metric (e.g., DALY per kilocalorie). This would provide information to consumers, regulators, and policy makers to simultaneously compare the overall human health burden of producing different types of protein. Such quantitative evaluations for the food processing industry can yield data-driven solutions to minimize the overall burden of human health in the food industry ultimately.

5.5 Conclusions

To understand the human health impacts of foodborne illnesses of beef consumption, and the environmental impacts and occupational hazards of beef slaughtering, we developed an interdisciplinary methodology to quantify the tradeoffs. The results show that the three sources of human health impact are of the same magnitude. Major contributors within each health burden source are evaluated and improvements for sustainable development of U.S. beef industry are identified. We also propose reductions in foodborne pathogens by resource-intensive food safety interventions should be considered jointly with environmental impacts and occupational hazards to prevent unintended shifts or increases in human health impact. As consumers and the beef slaughtering industry focuses on sustainability in addition to employee and beef microbiological safety, this study has particular relevance for considering the potential for trade-offs between food safety, occupational hazards, and environmental impacts.
5.6 Appendix: Supporting information

The method devised in this manuscript (Figure 5.1) allows to compare the three important impacts on human health on the same metric as disease burden expressed in DALY. The three impacts are separated into three parts of this supplementary information for a more detailed description. The **Part 1** introduces the calculations and data sources of U.S. beef foodborne illnesses on human health. The **Part 2** introduces the system boundary and data sources used in the life cycle assessment for calculating environmental impacts on human health from U.S. beef slaughtering. The **Part 3** provides a step-by-step demonstration on calculating occupational hazards on human health from U.S. beef slaughtering.

### 5.6.1 Part 1: Disease burden from the U.S. beef foodborne illnesses

Table S5.1 Foodborne illnesses attributed to beef by 9 major pathogens

<table>
<thead>
<tr>
<th>Pathogens*</th>
<th>Total Illnesses by 17 food commodities</th>
<th>Minimun, (%)†</th>
<th>Most probable, (%)†</th>
<th>Maximum, beef (%)†</th>
<th>Minimum, (number of illnesses)</th>
<th>Most probable, (number of illnesses)</th>
<th>Maximum, (number of illnesses)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacillus cereus</strong></td>
<td>63,400</td>
<td>5.4</td>
<td>8.6</td>
<td>13.9</td>
<td>3,424</td>
<td>5,452</td>
<td>8,813</td>
</tr>
<tr>
<td><strong>Clostridium perfringens</strong></td>
<td>965,958</td>
<td>16.3</td>
<td>33.1</td>
<td>41.1</td>
<td>157,451</td>
<td>319,732</td>
<td>397,009</td>
</tr>
<tr>
<td><strong>E. coli O157</strong></td>
<td>63,153</td>
<td>33</td>
<td>39.4</td>
<td>41.3</td>
<td>20,840</td>
<td>24,882</td>
<td>26,082</td>
</tr>
<tr>
<td><strong>Listeria monocytogenes</strong></td>
<td>1,591</td>
<td>1.2</td>
<td>2.2</td>
<td>35.6</td>
<td>19</td>
<td>35</td>
<td>566</td>
</tr>
<tr>
<td><strong>Norovirus</strong></td>
<td>5,461,731</td>
<td>1.2</td>
<td>2.9</td>
<td>15.3</td>
<td>65,541</td>
<td>158,390</td>
<td>835,645</td>
</tr>
<tr>
<td><strong>Salmonella</strong></td>
<td>1,029,382</td>
<td>3.5</td>
<td>7.3</td>
<td>14.9</td>
<td>36,028</td>
<td>75,145</td>
<td>153,378</td>
</tr>
<tr>
<td><strong>Staphylococcus aureus</strong></td>
<td>241,148</td>
<td>3.9</td>
<td>7.7</td>
<td>18.9</td>
<td>9,405</td>
<td>18,568</td>
<td>45,577</td>
</tr>
<tr>
<td><strong>E. coli, non-O157 STE</strong></td>
<td>112,752</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>33,487</td>
<td>33,487</td>
<td>33,487</td>
</tr>
<tr>
<td><strong>Shigella spp.</strong></td>
<td>131,254</td>
<td>2.1</td>
<td>3.2</td>
<td>7.4</td>
<td>2,756</td>
<td>4,200</td>
<td>9,713</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>9,638,301</td>
<td>3.6</td>
<td>6.6</td>
<td>15.8</td>
<td>346,979</td>
<td>636,128</td>
<td>1,522,852</td>
</tr>
</tbody>
</table>

Note: Only 9 major pathogens among 31 major pathogens are related to beef consumption and are listed here (Painter et al., 2013).
† Minimum, most probable, and maximum are the likelihoods of foodborne illness associated with beef.

Table S5.2 Disease burden (DALY) per 1000 foodborne illnesses related to the seven primary pathogens from two published studies

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>YLD (1,000 illnesses)</th>
<th>YLL (1,000 illnesses)</th>
<th>Total DALY (1,000 illnesses)</th>
<th>Number of illnesses</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clostridium perfringens</strong></td>
<td>3,000</td>
<td>900</td>
<td>3,900</td>
<td>966,000</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>E. coli O157</strong></td>
<td>430</td>
<td>800</td>
<td>1,230</td>
<td>63,000</td>
<td>6.8</td>
</tr>
<tr>
<td><strong>Listeria monocytogenes</strong></td>
<td>180</td>
<td>8,600</td>
<td>8,780</td>
<td>1,600</td>
<td>112.5</td>
</tr>
<tr>
<td><strong>Norovirus</strong></td>
<td>7,500</td>
<td>2,400</td>
<td>9,900</td>
<td>5,461,700</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Salmonella</strong></td>
<td>24,300</td>
<td>8,600</td>
<td>32,900</td>
<td>1,027,600</td>
<td>23.6</td>
</tr>
<tr>
<td><strong>Bacillus cereus</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Staphylococcus aureus</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Note:

i. Calculations explanation:
   - column (1) + column (2) = column (3)
   - column (1) ÷ column (4) = column (5)
   - column (2) ÷ column (4) = column (6)
   - column (3) ÷ column (4) = column (7)

ii. Escherichia coli, non-O157 STEC and Shigella spp. listed in Table S1 were excluded in Table S2 due to insufficient data to calculate their DALY per 1000 illnesses.

iii. The DALY/1000 illnesses of the five pathogens (i.e., Clostridium perfringens, E. coli O157, Listeria monocytogenes, Norovirus, Salmonella) were calculated based on DALY of foodborne pathogens from Scallan et al. (Scallan et al., 2015b) as it is more U.S.-region relevant. For the other two pathogens (Bacillus cereus and Staphylococcus aureus) unavailable in the work of Scallan et al., the data were obtained based on DALY foodborne pathogens from another study in Netherland by Havelaar and colleagues. (Havelaar et al., 2012)

iv. Total DALY is not exactly equal to the sum of YLD and YLL due to rounding errors in the original literature.
### Table S5.3 Disease burden (DALY) of foodborne illnesses attributed to 1000 kg live cattle weight by major pathogens.

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Minimum (number of illnesses)</th>
<th>Most probable (number of illnesses)</th>
<th>Maximum (number of illnesses)</th>
<th>DALY (1000 illnesses)</th>
<th>Minimum (DALY/1000 kg LW)</th>
<th>Most probable (DALY/1000 kg LW)</th>
<th>Maximum (DALY/1000 kg LW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Bacillus cereus</em></td>
<td>3,424</td>
<td>5,452</td>
<td>8,813</td>
<td>2.3</td>
<td>4.0E-07</td>
<td>6.4E-07</td>
<td>1.0E-06</td>
</tr>
<tr>
<td><em>Clostridium perfringens</em></td>
<td>157,451</td>
<td>319,732</td>
<td>397,009</td>
<td>4.1</td>
<td>3.3E-05</td>
<td>6.8E-05</td>
<td>8.4E-05</td>
</tr>
<tr>
<td><em>E. coli O157</em></td>
<td>20,840</td>
<td>24,882</td>
<td>26,082</td>
<td>19.0</td>
<td>2.0E-05</td>
<td>2.4E-05</td>
<td>2.5E-05</td>
</tr>
<tr>
<td><em>Listeria monocytogenes</em></td>
<td>19</td>
<td>35</td>
<td>566</td>
<td>5.531.1</td>
<td>5.4E-06</td>
<td>9.9E-06</td>
<td>1.6E-04</td>
</tr>
<tr>
<td>Norovirus</td>
<td>65,541</td>
<td>158,390</td>
<td>835,645</td>
<td>1.8</td>
<td>6.1E-06</td>
<td>1.5E-05</td>
<td>7.7E-05</td>
</tr>
<tr>
<td><em>Salmonella, non-typhoidal</em></td>
<td>36,028</td>
<td>75,145</td>
<td>153,378</td>
<td>32.0</td>
<td>5.9E-05</td>
<td>1.2E-04</td>
<td>2.5E-04</td>
</tr>
<tr>
<td><em>Staphylococcus aureus</em></td>
<td>9,405</td>
<td>18,568</td>
<td>45,577</td>
<td>2.6</td>
<td>1.2E-06</td>
<td>2.5E-06</td>
<td>6.0E-06</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>292,708</strong></td>
<td><strong>602,204</strong></td>
<td><strong>1,467,070</strong></td>
<td><strong>1.3E-04</strong></td>
<td><strong>2.4E-04</strong></td>
<td><strong>6.0E-04</strong></td>
<td></td>
</tr>
</tbody>
</table>

Note: Since the estimates of foodborne illnesses by major pathogens were based on the 2006 US population, the annual beef production in live weight in the year of 2006 was used; total live cattle weight for slaughter in 2006 (19601.5 million kilograms) obtained from USDA ERS (USDA ERS, 2016) was used to normalize DALY caused by beef foodborne illnesses.
5.6.2 Part 2: Disease burden of environmental impacts from the U.S. beef slaughtering

The inventory data listed below are collected from two beef slaughterhouses in 2016 and weighted by the head count of cattle processed by the two plants. The functional unit in this inventory is 1000 kg live weight beef. The chemicals applied in beef slaughterhouse include chemicals for cleaning and sanitizer (e.g., cannon foam, sodium hypochlorite, heavy-duty high foaming caustic), chemicals for antimicrobial treatment (e.g., lactic acid, peracetic acid), chemicals for general processing (e.g., rendering magnesium hydroxide, sulfuric acid), oils and lubricants (e.g., hydraulic oil, industrial gear oil). The beef slaughterhouses applied around dozens of various chemicals and we collected all chemical usage from their annual plant inventory records. However, most of those chemicals and proprietary and are not available in the existing LCA database and we are not allowed to provide the commercial name of those chemicals. Therefore, we classify those chemicals based on their ingredients into two categories: organic and inorganic chemicals, which are available in Ecoinvent v3.3 database. Ecoinvent v3.3 average 20 of most popular organic and inorganic chemicals, respectively, to represent general cases of inventory data of organic and inorganic chemicals.
Table S5.4 Data collection of onsite resources consumed and solid waste input

<table>
<thead>
<tr>
<th>Resources/processes</th>
<th>Value</th>
<th>Unit</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for processing</td>
<td>53.2</td>
<td>kWh/1000 kg LW</td>
<td>Electricity bills</td>
</tr>
<tr>
<td>Electricity for cooling</td>
<td>27.8</td>
<td>kWh/1000 kg LW</td>
<td>Onsite metering</td>
</tr>
<tr>
<td>Natural gas for heating water</td>
<td>674.8</td>
<td>MJ/1000 kg LW</td>
<td>Natural gas bills</td>
</tr>
<tr>
<td>Natural gas for human comfort (winter only)</td>
<td>495.4</td>
<td>MJ/1000 kg LW</td>
<td>Natural gas bills</td>
</tr>
<tr>
<td>Chemicals for overnight cleaning</td>
<td>0.8</td>
<td>kg/1000 kg LW</td>
<td>Purchasing orders</td>
</tr>
<tr>
<td>Chemicals for cleaning, sanitizer, disinfectant at processing shift</td>
<td>3.2</td>
<td>kg/1000 kg LW</td>
<td>Purchasing orders</td>
</tr>
<tr>
<td>Manure disposal</td>
<td>24.0</td>
<td>kg/1000 kg LW</td>
<td>Plant discharge reports</td>
</tr>
<tr>
<td>Packaging materials</td>
<td>11.3</td>
<td>kg/1000 kg LW</td>
<td>Supplier data</td>
</tr>
<tr>
<td>Chemicals for other uses (e.g., Boilers scale treatment, Marking ink)</td>
<td>0.02</td>
<td>kg/1000 kg LW</td>
<td>Purchasing orders</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>3,741.2</td>
<td>L/1000 kg LW</td>
<td>Plant discharge reports</td>
</tr>
<tr>
<td>Water supply</td>
<td>3,741.2</td>
<td>L/1000 kg LW</td>
<td>Onsite metering</td>
</tr>
<tr>
<td>Transportation</td>
<td>5.4</td>
<td>(ton*km)/1000 kg LW</td>
<td>Personal communication</td>
</tr>
<tr>
<td>General waste (e.g., plastics, organic waste)</td>
<td>12.0</td>
<td>kg/1000 kg LW</td>
<td>Solid waste invoices</td>
</tr>
</tbody>
</table>
Table S5.5 Life cycle inventory background processes and databases chosen for evaluating environmental impacts of beef slaughtering

<table>
<thead>
<tr>
<th>Resources/processes</th>
<th>Process name in the database</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for processing</td>
<td>Electricity, at Grid, US, 2008 NREL/RNA U U*</td>
<td>US-EI 2.2 (LTS, 2016)</td>
</tr>
<tr>
<td>Electricity for cooling</td>
<td>Electricity, at Grid, US, 2008 NREL/RNA U U*</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Natural gas for heating water and steam</td>
<td>Natural gas, burned in boiler condensing modulating &gt;100kW/US- US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Chemicals for cleaning, sanitizer, disinfectant at processing shift</td>
<td>Chemicals organic, at plant/GLO US-EI U; Chemicals inorganic, at plant/GLO US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Chemicals for other uses (e.g., Boilers scale treatment, Marking ink)</td>
<td>Chemicals organic, at plant/GLO US-EI U; Chemicals inorganic, at plant/GLO US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Water supply</td>
<td>Tap water, at user/US- US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>General waste (e.g., plastics, organic waste)</td>
<td>Process-specific burdens, sanitary landfill/US US-EI U; Disposal, plastics, mixture, 0% water, to sanitary landfill/US US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>Onsite data collected from a wastewater treatment plant specifically for slaughterhouse wastewater (Li et al., 2018)</td>
<td>(Li et al., 2018a)</td>
</tr>
</tbody>
</table>

Note: * The water footprint of the electricity from hydropower plant was reported as 45 m$^3$/kWh in US-EI database. This number represents the total amount of water passing through hydropower turbines. In a newer study evaluating water footprint from various types of electricity generation technologies, water footprint of hydropower was estimated as the evaporation of the hydropower reservoirs for electricity generation, reporting as 0.055 m$^3$/kWh on average (Mekonnen et al., 2015). As counting all the water running over hydropower turbines are overestimating the water footprint of hydropower, the data (0.055 m$^3$/kWh from hydropower) from Mekonnen et al. (2015) was applied.

† Organic waste in the general waste category typically includes hairs and other organic meat scrappers.
Table S5.6 Inventory background processes and databases chosen for evaluating environmental impacts of rendering

<table>
<thead>
<tr>
<th>Resources</th>
<th>Value (kg/1000 kg LW)</th>
<th>Unit</th>
<th>Process name in the database</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>42.00</td>
<td>MJ/1000 kg LW</td>
<td>US-EI 2.2</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>647.60</td>
<td>L/1000 kg LW</td>
<td>Tap water, at user/US- US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Chemicals, inorganic</td>
<td>1.75</td>
<td>kg/1000 kg LW</td>
<td>Chemicals inorganic, at plant/GLO US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Chemicals, organic</td>
<td>0.10</td>
<td>kg/1000 kg LW</td>
<td>Chemicals organic, at plant/GLO US-EI U;</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Oils and lubricants for rendering</td>
<td>0.19</td>
<td>kg/1000 kg LW</td>
<td>Lubricating oil, at plant/US-US-EI U</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>647.60</td>
<td>L/1000 kg LW</td>
<td>Onsite data collected from a wastewater treatment plant specifically for slaughterhouse wastewater</td>
<td>(Li et al., 2018a)</td>
</tr>
</tbody>
</table>

Note: By-products (e.g., blood, various tissues, bones and inedible parts) are processed in the rendering process.

Table S5.7 Inventory background processes and databases chosen for evaluating environmental impacts of manure disposal and management

<table>
<thead>
<tr>
<th>Manure</th>
<th>Value (kg/1 kg manure)</th>
<th>Process name in the database</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions due to spreading manure</td>
<td>1</td>
<td>Solid manure loading and spreading, by hydraulic loader and spreader {CH}</td>
<td>Alloc Def, U</td>
</tr>
<tr>
<td>Emissions due to manure management</td>
<td>1</td>
<td>Manure management mix, region 5, per kg FPCM</td>
<td>US-EI 2.2</td>
</tr>
<tr>
<td>Credits for fertilizer replacement</td>
<td>1.7E-03</td>
<td>Nitrogen fertiliser, as N {GLO}</td>
<td>nutrient supply from compost</td>
</tr>
</tbody>
</table>

Note: The emissions from animal slurry due to spreading manure activities as well as emissions from manure management practices (e.g., storage and land-application) are considered. Excrement and intestinal contents are considered in our work as yard and paunch manure, respectively.
Table S5.8 Process contribution analysis of total environmental impacts on human health
(DALY/1000 kg LW beef)

<table>
<thead>
<tr>
<th>Processes</th>
<th>Global warming</th>
<th>Matter formaton</th>
<th>Human toxicity</th>
<th>Water consumption†</th>
<th>Ozone formaton</th>
<th>Ozone depletiion</th>
<th>Ionizing radiatioon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>2.2E-04</td>
<td>2.2E-05</td>
<td>9.6E-05</td>
<td>1.2E-05</td>
<td>1.2E-06</td>
<td>1.5E-07</td>
<td>3.8E-08</td>
</tr>
<tr>
<td>Electricity (onsite)</td>
<td>5.7E-05</td>
<td>5.2E-05</td>
<td>6.6E-05</td>
<td>2.5E-06</td>
<td>2.4E-07</td>
<td>9.0E-09</td>
<td>3.4E-09</td>
</tr>
<tr>
<td>Natural gas (onsite)</td>
<td>9.6E-05</td>
<td>9.5E-05</td>
<td>1.3E-05</td>
<td>3.0E-07</td>
<td>7.3E-07</td>
<td>9.0E-09</td>
<td>4.4E-09</td>
</tr>
<tr>
<td>Total chemicals</td>
<td>8.6E-06</td>
<td>8.3E-06</td>
<td>1.4E-06</td>
<td>3.0E-08</td>
<td>0.8E-08</td>
<td>7.4E-09</td>
<td>9.9E-10</td>
</tr>
<tr>
<td>Manure (land-applied)</td>
<td>1.2E-05</td>
<td>1.0E-05</td>
<td>2.5E-08</td>
<td>1.5E-08</td>
<td>9.0E-09</td>
<td>8.3E-09</td>
<td>1.0E-08</td>
</tr>
<tr>
<td>Packaging materials</td>
<td>6.2E-06</td>
<td>6.2E-06</td>
<td>1.5E-06</td>
<td>7.2E-08</td>
<td>9.0E-09</td>
<td>5.2E-09</td>
<td>2.1E-10</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>9.4E-06</td>
<td>9.4E-06</td>
<td>4.1E-07</td>
<td>3.1E-08</td>
<td>8.3E-08</td>
<td>2.6E-09</td>
<td>5.2E-09</td>
</tr>
<tr>
<td>Rendering</td>
<td>1.8E-05</td>
<td>1.8E-05</td>
<td>2.6E-06</td>
<td>8.3E-08</td>
<td>8.3E-08</td>
<td>8.1E-09</td>
<td>1.8E-10</td>
</tr>
<tr>
<td>Water supply (onsite)</td>
<td>5.4E-06</td>
<td>5.4E-06</td>
<td>3.7E-06</td>
<td>2.5E-11</td>
<td>2.6E-11</td>
<td>2.6E-11</td>
<td>2.6E-11</td>
</tr>
<tr>
<td>General waste (landfill)</td>
<td>2.1E-07</td>
<td>2.1E-07</td>
<td>4.4E-09</td>
<td>7.1E-10</td>
<td>6.1E-11</td>
<td>6.1E-11</td>
<td>6.1E-11</td>
</tr>
<tr>
<td>Transportation</td>
<td>9.3E-07</td>
<td>9.3E-07</td>
<td>3.0E-08</td>
<td>3.4E-09</td>
<td>3.4E-09</td>
<td>3.8E-10</td>
<td>3.8E-10</td>
</tr>
</tbody>
</table>

Note: * Negative signs under the land-applied manure process are due to the environmental impact benefits from the avoided product (i.e., fertilizers).

† Characterization factor of water consumption on human health were adjusted from world average (2.2E-06 DALY/m³) to United States Hierarchist (9.8E-07 DALY/m³) to better represent geographic feature (Huijbregts et al., 2016).
Table S5.9 Substance contribution analysis of human toxicity on human health from ReCiPe 2016 method (Huijbregts et al., 2017)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Compartment</th>
<th>DALY/1000 kg LW beef</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Water</td>
<td>1.0E-05</td>
<td>46%</td>
</tr>
<tr>
<td>Chromium VI</td>
<td>Water</td>
<td>5.3E-06</td>
<td>24%</td>
</tr>
<tr>
<td>Zinc</td>
<td>Soil</td>
<td>4.8E-06</td>
<td>22%</td>
</tr>
<tr>
<td>Lead</td>
<td>Water</td>
<td>2.0E-07</td>
<td>1%</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Soil</td>
<td>1.9E-07</td>
<td>1%</td>
</tr>
<tr>
<td>Chromium VI</td>
<td>Air</td>
<td>1.5E-07</td>
<td>1%</td>
</tr>
<tr>
<td>Chromium VI</td>
<td>Soil</td>
<td>1.2E-07</td>
<td>1%</td>
</tr>
<tr>
<td>Remaining substances (&lt;5%)*</td>
<td>7.6E-07</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Total of all compartments</td>
<td>2.2E-05</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Note: * For brevity, numerous substances that have minimal impacts on human toxicity (< 5%) are accumulated as “remaining substances”.

Table S5.10 Substance contribution analysis of human toxicity on human health from USEtox method (Marian Bijster et al., 2017)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Compartment</th>
<th>DALY/1000 kg LW beef</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Soil</td>
<td>2.9E-05</td>
<td>28%</td>
</tr>
<tr>
<td>Chromium VI</td>
<td>Water</td>
<td>2.5E-05</td>
<td>23%</td>
</tr>
<tr>
<td>Mercury</td>
<td>Air</td>
<td>8.7E-06</td>
<td>8%</td>
</tr>
<tr>
<td>Mercury</td>
<td>Soil</td>
<td>6.8E-06</td>
<td>6%</td>
</tr>
<tr>
<td>Lead</td>
<td>Soil</td>
<td>6.6E-06</td>
<td>6%</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Soil</td>
<td>5.5E-06</td>
<td>5%</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Water</td>
<td>5.0E-06</td>
<td>5%</td>
</tr>
<tr>
<td>Barium</td>
<td>Water</td>
<td>3.9E-06</td>
<td>4%</td>
</tr>
<tr>
<td>Zinc</td>
<td>Water</td>
<td>3.9E-06</td>
<td>4%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Soil</td>
<td>3.4E-06</td>
<td>3%</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Water</td>
<td>2.0E-06</td>
<td>2%</td>
</tr>
<tr>
<td>Nickel</td>
<td>Water</td>
<td>1.7E-06</td>
<td>2%</td>
</tr>
<tr>
<td>Remaining substances (&lt;5%)*</td>
<td>4.6E-06</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Total of all compartments</td>
<td>1.1E-04</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

* For brevity, numerous substances that have minimal impacts on human toxicity (< 5%) are accumulated as “remaining substances”.
Table S5.11 Difference contribution by substance of human toxicity on human health between USEtox 2.0 and ReCiPe 2016 methods.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Compartment</th>
<th>Difference* (DALY/1000 kg LW beef)</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Soil</td>
<td>2.5E-05</td>
<td>29%</td>
</tr>
<tr>
<td>Chromium VI</td>
<td>Water</td>
<td>1.9E-05</td>
<td>23%</td>
</tr>
<tr>
<td>Mercury</td>
<td>Air</td>
<td>8.7E-06</td>
<td>10%</td>
</tr>
<tr>
<td>Mercury</td>
<td>Soil</td>
<td>6.8E-06</td>
<td>8%</td>
</tr>
<tr>
<td>Lead</td>
<td>Soil</td>
<td>6.6E-06</td>
<td>8%</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Soil</td>
<td>5.3E-06</td>
<td>6%</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Water</td>
<td>5.0E-06</td>
<td>6%</td>
</tr>
<tr>
<td>Barium</td>
<td>Water</td>
<td>3.9E-06</td>
<td>5%</td>
</tr>
<tr>
<td>Zinc</td>
<td>Water</td>
<td>-6.3E-06</td>
<td>-7%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Soil</td>
<td>3.4E-06</td>
<td>4%</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Water</td>
<td>2.0E-06</td>
<td>2%</td>
</tr>
<tr>
<td>Nickel</td>
<td>Water</td>
<td>1.7E-06</td>
<td>2%</td>
</tr>
</tbody>
</table>

Remaining substances (5%) 3.9E-06 5%
Total of all compartments 8.5E-05 100%

Note: * Difference is defined as the impact from the substance from USEtox minus the impact from the same substance and same compartment from ReCiPe method. Positive sign means the same substance via the same compartment based on USEtox method has larger impact than that based on ReCiPe and vice versa.
5.6.3 Part 3: Disease burden of occupational hazards from the U.S. beef slaughtering

The work on developing WE_DALY by Scanlon et al. (Scanlon et al., 2013) was briefly introduced here to help understanding on how WE_DALY was applied to calculate occupational risks in our study. First, WE_DALY is calculated in Equation (5-1). For each NAICS code \( n \), \( YLD_n \) represents healthy life lost in years due to work-related injuries and illnesses while \( YLL_n \) represents early mortality among the worker population.

\[
WE_{DALY} = YLD + YLL_n \tag{5-1}
\]

\( YLD_n \) is calculated summarizing results obtained from Equations (5-2), (5-3), (5-4) depending on different nature of nonfatal injuries and cases and summarized in Equation (5-5).

For short-term (ST) injuries and illnesses,

\[
YLD_{n,ST} = \sum_{c=1}^{x} \sum_{a=1}^{3} I_{c,a,ST} \times W_{c,ST} \times D_{c,a,ST} \tag{5-2}
\]

For life-long (LL) injuries and illnesses,

\[
YLD_{n,LL} = \sum_{c=1}^{x} \sum_{a=1}^{3} I_{c,a,LL} \times W_{c,LL} \times D_{c,a,LL} \tag{5-3}
\]

For injuries and illnesses containing both LL and ST duration.

\[
YLD_{n,LL+ST} = (YLD_{n,LL} \times (\% LL)) + (YLD_{n,ST} \times (\% ST)) \tag{5-4}
\]

Then Equation (5) is applied to summarize total YLD for each NAICS code \( n \) from three types of YLD.
\[ YLD_n = YLD_{n,LL} + YLD_{n,ST} + YLD_{n,LL+ST} \] (5-5)

Where \( I_{c,a,ST} \) or \( I_{c,a,LL} \) stands for total cases of short-term (ST) or life-long (LL) nonfatal injuries and illnesses, respectively, for each Bureau of Labor Statistics (BLS) nature code (c) at each age strata (a); nature of injuries or illnesses can be classified by BLS nature code developed by the Occupational Injury and Illnesses Classification System (OIICS). \( W_{c,ST} \) or \( W_{c,LL} \) is the short-term or life-long disability weight, respectively, for each nature code (c). \( W_{c,ST} \) or \( W_{c,LL} \) ranges from 0 to 1, as “0” being perfect health and “1” being equivalent death. \( D_{c,a,ST} \) is the duration of nature code (c) for short-term injuries and illnesses per age strata (a) while \( D_{c,a,LL} \) is the duration of nature code for life-long injuries and illnesses per age strata (a). \( x \) denotes the number of types of nonfatal injuries and illnesses.

\( YLL_n \) is calculated using the total cases of fatal injuries per each age strata \( (N_a) \) multiplying their average life remaining in years per corresponding age strata \( (L_a) \).

\[ YLL_n = \sum_{a=1}^{3} N_a \times L_a \] (5-6)

The following tables demonstrate the calculation of WE-DALY of three interested NAICS codes step by step.
Step 1: Obtain total cases of nonfatal injuries and illnesses for each BLS nature code (Ic) for the three involved NAICS codes from BLS (Bureau of Labor Statistics and Injuries, Illnesses, 2015a) shown in Table S3.1.

Table S5.12 Number of nonfatal injuries and illnesses of three involved NAICS codes

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>Type of injury or illnesses</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>Sprains, strains, tears</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>330</td>
</tr>
</tbody>
</table>

| Meat processed from carcasses (311612) | Sprains, strains, tears | 450 |
|                                         | Fractures                | 120 |
|                                         | Cuts, lacerations        | 200 |
|                                         | Punctures                | -   |
|                                         | Bruises, contusions      | 160 |
|                                         | Heat burns               | 20  |
|                                         | Chemical burns           | 30  |
|                                         | Amputations              | 30  |
|                                         | Carpal tunnel syndrome   | 40  |
|                                         | Tendonitis               | -   |
|                                         | Multiple traumatic injuries and disorders | 70 |
|                                         | Soreness, pain           | 230 |
|                                         | Unspecified nonfatal injuries | 230 |

| Janitorial services (56172)* (Cleaning and sanitation activities in beef slaughterhouses fall into the categories as well.) | Sprains, strains, tears | 3,510 |
|                                                                                                                   | Fractures                | 660  |
|                                                                                                                   | Cuts, lacerations        | 610  |
|                                                                                                                   | Punctures                | 120  |
|                                                                                                                   | Bruises, contusions      | 1,130 |
|                                                                                                                   | Heat burns               | 20   |
|                                                                                                                   | Chemical burns           | 90   |
|                                                                                                                   | Amputations              | -    |
|                                                                                                                   | Carpal tunnel syndrome   | -    |
|                                                                                                                   | Tendonitis               | -    |
|                                                                                                                   | Multiple traumatic injuries and disorders | 110 |
|                                                                                                                   | Soreness, pain           | 1,790|
|                                                                                                                   | Unspecified nonfatal injuries | 1,190 |
Note: “-” represents either situation “no injuries and illnesses” or situation “data not met by BLS criteria.”

* Janitorial Services (NAICS 56172) are primarily related to cleaning services across various types of buildings and industry. Projected number of janitorial workers required for beef slaughtering industry is provided in Table S3.10 (a).

**Step 2:**
1) Obtain total cases of nonfatal injuries and illnesses on BLS age strata\(^{10}\) (Table S3.2 (a));
2) Convert it into WHO age strata so that disability weights from WHO can be applied in this study (Table S3.2 (b));
3) Calculate age-weighted multiplier to estimate total cases with WHO age distribution (Table S3.2 (c)).

Table S5.13 Total cases of nonfatal injuries and illnesses by BLS age strata(Bureau of Labor Statistics and Injuries, Illnesses, 2015b)

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>Total cases</th>
<th>16-19</th>
<th>20-24</th>
<th>25-34</th>
<th>35-44</th>
<th>45-54</th>
<th>55-64</th>
<th>65 and over</th>
<th>not reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>1,290</td>
<td>-</td>
<td>11</td>
<td>0</td>
<td>270</td>
<td>330</td>
<td>360</td>
<td>170</td>
<td>50</td>
</tr>
<tr>
<td>Meat processed from carcasses (311612)</td>
<td>1,540</td>
<td>30</td>
<td>10</td>
<td>0</td>
<td>300</td>
<td>350</td>
<td>390</td>
<td>290</td>
<td>30</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>9,420</td>
<td>150</td>
<td>65</td>
<td>0</td>
<td>60</td>
<td>50</td>
<td>10</td>
<td>50</td>
<td>380</td>
</tr>
</tbody>
</table>

Table S5.14 Conversion of total cases of nonfatal injuries and illnesses by BLS age strata to WHO age strata.

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>Total cases</th>
<th>15 to 44</th>
<th>45 to 59</th>
<th>60 to 80</th>
<th>not reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>1,290</td>
<td>710</td>
<td>445</td>
<td>135</td>
<td>-</td>
</tr>
<tr>
<td>Meat processed from carcasses (311612)</td>
<td>1,540</td>
<td>780</td>
<td>535</td>
<td>175</td>
<td>50</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>9,420</td>
<td>4,410</td>
<td>3,635</td>
<td>1,105</td>
<td>270</td>
</tr>
</tbody>
</table>
Table S5.15 WHO age strata weighted multipliers for nonfatal injuries and illnesses

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>15 to 44</th>
<th>45 to 59</th>
<th>60 to 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>55.0%</td>
<td>34.5%</td>
<td>10.5%</td>
</tr>
<tr>
<td>Meat processed from carcasses (311612)</td>
<td>52.3%</td>
<td>35.9%</td>
<td>11.7%</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>48.2%</td>
<td>39.7%</td>
<td>12.1%</td>
</tr>
</tbody>
</table>

**Step 3:** Allocate life-long and short-term nonfatal injuries or illnesses

Table S5.16 Partitioning coefficient of life-long and short-term nonfatal injuries or illnesses

<table>
<thead>
<tr>
<th>Types of injury or illnesses</th>
<th>Life-long</th>
<th>Short-term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprains, strains, tears</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Fractures</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>Cuts, lacerations</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Puncture wounds, except gunshot wounds</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Bruises, contusions</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Heat burns</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Amputations</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Carpal tunnel syndrome</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>Soreness, pain</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Unspecified nonfatal injuries</td>
<td>33%</td>
<td>67%</td>
</tr>
</tbody>
</table>

The assignment of life-long and short-term injuries mainly was retrieved from Scanlon et al. (2013) with modifications. For example: for the injury “fractures”, 2% of fractures were assigned as life-long injuries while 98% of fractures were assigned as short-term injuries.
Table S5.17 Details regarding the partition of life-long and short-term injuries using BLS nature codes

<table>
<thead>
<tr>
<th>Type of injuries and illnesses</th>
<th>Duration assignment</th>
<th>Assumptions or matched BLS nature codes for duration assignment (BLS codes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprains, strains, tears</td>
<td>100% Short-term</td>
<td>Sprains- strains- tears (021)</td>
</tr>
<tr>
<td>Fractures</td>
<td>98% Short-term</td>
<td>Fractures (012)</td>
</tr>
<tr>
<td>Fractures</td>
<td>2% Life-long</td>
<td>Fractures (012)</td>
</tr>
<tr>
<td>Cuts, lacerations</td>
<td>100% Short-term</td>
<td>Cuts- lacerations (034)</td>
</tr>
<tr>
<td>Puncture wounds, except gunshot wounds</td>
<td>100% Short-term</td>
<td>Punctures- except bites (037)</td>
</tr>
<tr>
<td>Bruises, contusions</td>
<td>100% Short-term</td>
<td>Bruises- contusions (043)</td>
</tr>
<tr>
<td>Heat burns</td>
<td>50% Short-term</td>
<td>Both long-term and short term is assumed to be 50%</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>50% Short-term</td>
<td>Both long-term and short term is assumed to be 50%</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>50% Life-long</td>
<td></td>
</tr>
<tr>
<td>Amputations</td>
<td>100% Life-long</td>
<td>Amputations (031)</td>
</tr>
<tr>
<td>Carpal tunnel syndrome</td>
<td>50% Short-term</td>
<td>Both long-term and short term is assumed to be 50%</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>100% Life-long</td>
<td>Musculoskeletal system and connective tissue diseases and disorders- unspecified (170)</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>60% Short-term</td>
<td>Multiple traumatic injuries and disorders- unspecified (080)</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>40% Life-long</td>
<td>Multiple traumatic injuries and disorders- unspecified (080)</td>
</tr>
<tr>
<td>Soreness, pain</td>
<td>100% Short-term</td>
<td>Other traumatic injuries and disorders- unspecified (090)</td>
</tr>
<tr>
<td>Non-classifiable</td>
<td>33% Life-long</td>
<td>Average on all types of long-term health states described above</td>
</tr>
<tr>
<td>Non-classifiable</td>
<td>67% Short-term</td>
<td>Average of all types of short-term health states described above</td>
</tr>
</tbody>
</table>
### Step 4: Calculate cases of nonfatal injuries and illnesses for each BLS nature code per age strata \( I_{ca} \) using age-weighted multipliers and partition coefficient of short-term and life-long injuries.

Table S5.18 Total cases of short-term nonfatal injuries per injury per age strata

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>Type of injury or illnesses</th>
<th>Number of short-term injuries by WHO age strata (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 to 44</td>
</tr>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>Sprains, strains, tears</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>64</td>
</tr>
<tr>
<td>Meat processed from carcasses (311612)</td>
<td>Sprains, strains, tears</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>42</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>Sprains, strains, tears</td>
<td>1,837</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>339</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>319</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>592</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>937</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>218</td>
</tr>
<tr>
<td>Industry (NAICS code)</td>
<td>Type of injury or illnesses</td>
<td>Number of life-long injuries by WHO age strata (a)</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>--------------------------------------</td>
<td>---------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 to 44</td>
</tr>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>Sprains, strains, tears</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>118</td>
</tr>
<tr>
<td>Meat processed from carcasses (311612)</td>
<td>Sprains, strains, tears</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>78</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>Sprains, strains, tears</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unspecified nonfatal injuries</td>
<td>405</td>
</tr>
</tbody>
</table>
Step 5: Calculate duration of short-term \( (D_{c,a,ST}) \) and life-long \( (D_{c,a,LL}) \) injuries and illnesses.

Table S5.20 Duration of short-term injuries and illnesses \( (D_{c,a,ST}) \) obtained from BLS (Bureau of Labor Statistics and Injuries, Illnesses, 2015c)

<table>
<thead>
<tr>
<th>Type of injuries or illnesses</th>
<th>Median days away from work (days)*</th>
<th>Duration (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprains, strains, tears</td>
<td>10</td>
<td>0.040</td>
</tr>
<tr>
<td>Fractures</td>
<td>32</td>
<td>0.128</td>
</tr>
<tr>
<td>Cuts, lacerations</td>
<td>3</td>
<td>0.012</td>
</tr>
<tr>
<td>Puncture wounds, except gunshot wounds</td>
<td>3</td>
<td>0.012</td>
</tr>
<tr>
<td>Bruises, contusions</td>
<td>4</td>
<td>0.016</td>
</tr>
<tr>
<td>Heat burns</td>
<td>4</td>
<td>0.016</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>3</td>
<td>0.012</td>
</tr>
<tr>
<td>Amputations</td>
<td>26</td>
<td>0.104</td>
</tr>
<tr>
<td>Carpal tunnel syndrome</td>
<td>28</td>
<td>0.112</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>14</td>
<td>0.056</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>10</td>
<td>0.040</td>
</tr>
<tr>
<td>Soreness, pain</td>
<td>7</td>
<td>0.028</td>
</tr>
<tr>
<td>Unspecified nonfatal injuries</td>
<td>15</td>
<td>0.060</td>
</tr>
</tbody>
</table>

* Median days away from work were multiplied by “1.46” to convert workdays into calendar days for calculating duration in years.

For example:

\[
\text{Duration for "Fractures" = 32 workdays} \times \frac{\text{calendar days}}{\text{workdays}} \div 365 \frac{\text{days}}{\text{year}} = 0.128 \text{ years}
\]

Table S5.21 Duration of life-long injuries and illnesses \( (D_{c,a,LL}) \) between male and female

<table>
<thead>
<tr>
<th>WHO age strata</th>
<th>Life remaining, Female (years)</th>
<th>Life remaining, Male (years)</th>
<th>Life remaining, Unisex (years)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>78.6</td>
<td>73.6</td>
<td>76.1</td>
</tr>
<tr>
<td>5 to 14</td>
<td>71.3</td>
<td>66.3</td>
<td>68.8</td>
</tr>
<tr>
<td>15 to 44</td>
<td>51.8</td>
<td>47.4</td>
<td>49.6</td>
</tr>
<tr>
<td>45 to 59</td>
<td>30.7</td>
<td>27.2</td>
<td>29.0</td>
</tr>
<tr>
<td>60 to 80</td>
<td>16.4</td>
<td>15.7</td>
<td>16.1</td>
</tr>
</tbody>
</table>

* Life remaining for unisex was calculated by averaging life remaining in years between female and male.
**Step 6:** Match disability weights of short-term and life-long nonfatal injuries with WHO health states (Salomon et al., 2015)

Table S5.22 Disability weights of short-term and life-long nonfatal injuries

<table>
<thead>
<tr>
<th>Type of injuries or illnesses from BLS</th>
<th>Life-long disability weight ( (W_{c,LL}) ), disability weight, ( (W_{c,ST}) ), average age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprains, strains, tears</td>
<td>-</td>
</tr>
<tr>
<td>Fractures</td>
<td>0.066</td>
</tr>
<tr>
<td>Cuts, lacerations</td>
<td>-</td>
</tr>
<tr>
<td>Puncture wounds, except gunshot wounds</td>
<td>-</td>
</tr>
<tr>
<td>Bruises, contusions</td>
<td>-</td>
</tr>
<tr>
<td>Heat burns</td>
<td>0.076</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>0.076</td>
</tr>
<tr>
<td>Amputations</td>
<td>0.131</td>
</tr>
<tr>
<td>Carpal tunnel syndrome</td>
<td>0.113</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>0.187</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>0.252</td>
</tr>
<tr>
<td>Soreness, pain</td>
<td>-</td>
</tr>
<tr>
<td>Unspecified nonfatal injuries</td>
<td>0.112</td>
</tr>
</tbody>
</table>
Table S5.23 Details regarding matching BLS nature codes with WHO health states and selecting disability weight

<table>
<thead>
<tr>
<th>Type of injuries and illnesses</th>
<th>BLS Nature code, version 2.01</th>
<th>Matched health states from Salomon et al. (2015)</th>
<th>Averaged disability weights from matched health states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprains, strains, tears</td>
<td>123</td>
<td>Other injuries of muscle and tendon (includes sprains, strains, and dislocations other than shoulder, knee, or hip)</td>
<td>0.008</td>
</tr>
<tr>
<td>Fractures</td>
<td>111</td>
<td>Fractures of clavicle, face bone, foot bones, hand, neck of femur, patella, pelvis, radius, skull, sternum, vertebral column, short term</td>
<td>0.098</td>
</tr>
<tr>
<td>Fractures</td>
<td>111</td>
<td>Fractures of clavicle, face bone, foot bones, hand, neck of femur, patella, pelvis, radius, skull, sternum, vertebral column, long term</td>
<td>0.066</td>
</tr>
<tr>
<td>Cuts, lacerations</td>
<td>132</td>
<td>Open wound: short term, with or without treatment</td>
<td>0.006</td>
</tr>
<tr>
<td>Puncture wounds, except gunshot wounds</td>
<td>133</td>
<td>Open wound: short term, with or without treatment</td>
<td>0.006</td>
</tr>
<tr>
<td>Bruises, contusions</td>
<td>143</td>
<td>Open wound: short term, with or without treatment</td>
<td>0.006</td>
</tr>
<tr>
<td>Heat burns</td>
<td>152</td>
<td>Burns: &lt;20%; &gt;20%, short term</td>
<td>0.228</td>
</tr>
<tr>
<td>Heat burns</td>
<td>152</td>
<td>Burns: &lt;20%; &gt;20%, long term</td>
<td>0.076</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>151</td>
<td>Burns: &lt;20%; &gt;20%, short term</td>
<td>0.228</td>
</tr>
<tr>
<td>Chemical burns</td>
<td>151</td>
<td>Burns: &lt;20%; &gt;20%, long term</td>
<td>0.076</td>
</tr>
<tr>
<td>Amputations</td>
<td>1311</td>
<td>Amputation of finger, thumb, arms, toe, legs</td>
<td>0.131</td>
</tr>
<tr>
<td>Carpal tunnel syndrome</td>
<td>2241</td>
<td>Injured nerves: short term</td>
<td>0.100</td>
</tr>
<tr>
<td>Carpal tunnel syndrome</td>
<td>2241</td>
<td>Injured nerves: long term</td>
<td>0.113</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>2735</td>
<td>Musculoskeletal problems: legs, arms, generalised (mild, moderate, severe)</td>
<td>0.187</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>18</td>
<td>Traumatic brain injury; Open wound; poisoning; severe chest injury; spinal cord; short term</td>
<td>0.276</td>
</tr>
<tr>
<td>Multiple traumatic injuries and disorders</td>
<td>18</td>
<td>Traumatic brain injury; Open wound; poisoning; severe chest injury; spinal cord; long term</td>
<td>0.252</td>
</tr>
<tr>
<td>Soreness, pain</td>
<td>1972</td>
<td>Proxy health state: Poisoning: short term, with or without treatment</td>
<td>0.163</td>
</tr>
<tr>
<td>Non-classifiable</td>
<td>9999</td>
<td>Average on all types of short-term health states described above</td>
<td>0.112</td>
</tr>
<tr>
<td>Non-classifiable</td>
<td>9999</td>
<td>Average of all types of long-term health states described above</td>
<td>0.114</td>
</tr>
</tbody>
</table>
**Step 7:** Calculate years lost due to disability (YLD) due to short-term and life-long injuries and illnesses

Table S5.24 Results of short-term and life-long YLD

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>Type of injury or illness</th>
<th>YLD (Short term)</th>
<th>YLD (life-long)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal (except poultry) slaughtering</td>
<td>Sprains, strains, tears</td>
<td>0.077</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>2</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0.0014</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>0.0058</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>0.055</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0.22</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>0.33</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>0.91</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unspecified injuries</td>
<td>1.5</td>
<td>480</td>
</tr>
<tr>
<td>Meat processed from carcasses</td>
<td>Sprains, strains, tears</td>
<td>0.14</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>1.5</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>0.014</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>0.015</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>0.036</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0.041</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0.22</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>0.46</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unspecified injuries</td>
<td>1</td>
<td>330</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>Sprains, strains, tears</td>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
<td>8.1</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Cuts, lacerations</td>
<td>0.044</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Punctures</td>
<td>0.0086</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bruises, contusions</td>
<td>0.11</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heat burns</td>
<td>0.036</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Chemical burns</td>
<td>0.12</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Amputations</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Carpal tunnel syndrome</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tendonitis</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Multiple traumatic injuries and disorders</td>
<td>0.73</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>Soreness, pain</td>
<td>8.6</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unspecified injuries</td>
<td>5.4</td>
<td>1700</td>
</tr>
</tbody>
</table>
**Step 8:** Calculate years of life lost (YLL)

Table S5.25 Results of YLL of interested NAICS codes

<table>
<thead>
<tr>
<th>BLS age strata</th>
<th>Average number of years remaining (L_a)</th>
<th>Number of fatalities for NAICS 31161 (N_a) (Bureau of Labor Statistics, 2017)</th>
<th>YLL, years (NAICS 31161)*</th>
<th>Number of fatalities for NAICS 5617 (N_a) (Bureau of Labor Statistics, 2017)</th>
<th>YLL, years (NAICS 5617)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 to 17</td>
<td>59.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18 to 19</td>
<td>57.5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>58</td>
</tr>
<tr>
<td>20 to 24</td>
<td>54.3</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>869</td>
</tr>
<tr>
<td>25 to 34</td>
<td>47.4</td>
<td>3</td>
<td>142</td>
<td>52</td>
<td>2,465</td>
</tr>
<tr>
<td>35 to 44</td>
<td>38.4</td>
<td>0</td>
<td>0</td>
<td>43</td>
<td>1,651</td>
</tr>
<tr>
<td>45 to 54</td>
<td>29.2</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>1,635</td>
</tr>
<tr>
<td>55 to 64</td>
<td>21.1</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>739</td>
</tr>
<tr>
<td>65 and over</td>
<td>13.6</td>
<td>0</td>
<td>0</td>
<td>31</td>
<td>422</td>
</tr>
<tr>
<td>Others</td>
<td>40.1†</td>
<td>5</td>
<td>201</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-</strong></td>
<td><strong>8</strong></td>
<td><strong>343</strong></td>
<td><strong>235</strong></td>
<td><strong>7,878</strong></td>
</tr>
</tbody>
</table>

* Fatality data of six-digit NAICS code are not available from BLS. Therefore, the “mother” NAICS codes 31161 and 5617 that have reported fatality data were used to estimate their years of life lost (YLL). Then attribution methods were applied to assign YLL to beef.

† 40.1 years is the average years remaining across BLS age strata.

**Step 9:** Attribution of YLD and YLL of NAICS codes 311611, 311612, and 31161 to beef.

NAICS 311611 and 311612 do not only include beef meat but also is composed of other meat except poultry, such as lambs and hogs. For NAICS “31161”, it does not only include red meat (beef, lamb, pork) but also poultry (e.g., broilers, turkeys).

Attribution based on live weight for slaughter from each type of animal was used to calculate the percentages shared by beef meat as illustrated in Table S3.9.
Table S5.26 Livestock and poultry data from USDA ERS (USDA ERS, 2016) and their corresponding NAICS codes

<table>
<thead>
<tr>
<th>Industry (five-digit NAICS code)</th>
<th>Industry (six-digit NAICS code)</th>
<th>Type of meat</th>
<th>Live weight for slaughter (million kg), 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal slaughtering and processing (NAICS 31161)</td>
<td>Animal slaughtering and meat processed from carcasses (except poultry) (NAICS 311611 and 311612)</td>
<td>Cattle (beef)</td>
<td>17,741</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calves (beef)</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hogs</td>
<td>14,827</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sheep and lambs</td>
<td>137</td>
</tr>
<tr>
<td>Poultry processing (NAICS 311615)</td>
<td></td>
<td>Broilers</td>
<td>24,118</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other chickens</td>
<td>366</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turkeys</td>
<td>3,183</td>
</tr>
</tbody>
</table>

For NAICS 311611 and 311612, % shared by beef based on the weight 54.3%

For NAICS 31161, % shared by beef based on the weight 29.4%

**Step 10:** Attribution of YLD and YLL of NAICS codes 56172 to sanitation workers in beef slaughterhouses

Based on the personal communication with the supervisor from a sanitation service crew, 200 janitorial workers on average are required to cover cleaning and sanitation tasks for a typical beef slaughterhouse that process about 4500 head of cattle on each weekday. Projected number of janitorial workers required for beef slaughtering industry is provided in Table S3.10 (a).

Table S5.27 Projected janitorial workers demographics for beef slaughtering industry

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual cattle headcount processed in a typical large-size beef slaughterhouse</td>
<td>1,173</td>
<td>Head (in 1,000) handled by 200 janitorial workers</td>
</tr>
<tr>
<td>Annual cattle head count in 2015 (USDA ERS, 2016)</td>
<td>29,204</td>
<td>Annual head (in 1,000)</td>
</tr>
<tr>
<td>Annual janitorial workers required for providing cleaning services for beef slaughtering industry</td>
<td>4,979</td>
<td>Projected number of janitorial workers</td>
</tr>
</tbody>
</table>

A number of fatalities from NAICS 56172 are not available in BLS. Therefore, fatalities data from its “mother” NAICS code 5617 was utilized first and then attributed to janitorial workers for beef slaughterhouses.
### Table S5.28 Results for NAICS 56172 and 5617

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>Cases/10,000 full time workers</th>
<th>Total cases</th>
<th>Total full-time workers (in thousands)</th>
<th>DALY/1,000 full-time workers</th>
<th>DALY due to janitorial services in beef slaughterhouses, 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Janitorial services (NAICS 56172)</td>
<td>127.5</td>
<td>9,410</td>
<td>738.0</td>
<td>3.2</td>
<td>16</td>
</tr>
<tr>
<td>Services to buildings and dwellings (NAICS 5617)</td>
<td>136.7</td>
<td>21,130</td>
<td>1,545.7</td>
<td>5.1</td>
<td>25</td>
</tr>
</tbody>
</table>

**Step 11:** Summary of DALY from occupational risks to the U.S. beef industry in 2015

Table S5.29 Summary of DALY from occupational risks connected to the U.S. beef slaughtering industry

<table>
<thead>
<tr>
<th>Industry (NAICS code)</th>
<th>DALY by NAICS code</th>
<th>DALY subcategory</th>
<th>Attribution method</th>
<th>DALY of beef in 2015</th>
<th>DALY per 1,000 kg LW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal (except poultry) slaughtering (311611)</td>
<td>973</td>
<td>YLD</td>
<td>Live cattle weight</td>
<td>529</td>
<td>3.0E-05</td>
</tr>
<tr>
<td>Meat processed from carcasses (311612)</td>
<td>917</td>
<td>YLD</td>
<td>Live cattle weight</td>
<td>498</td>
<td>2.8E-05</td>
</tr>
<tr>
<td>Animal slaughtering and processing (31161)</td>
<td>150</td>
<td>YLL</td>
<td>Live cattle weight</td>
<td>101</td>
<td>8.8E-07</td>
</tr>
<tr>
<td>Janitorial services (56172)</td>
<td>2,330</td>
<td>YLD</td>
<td>Number of janitorial workers</td>
<td>16</td>
<td>5.7E-06</td>
</tr>
<tr>
<td>Services to buildings and dwellings (5617)</td>
<td>7,878</td>
<td>YLL</td>
<td>Number of janitorial workers</td>
<td>25</td>
<td>1.4E-06</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1169</strong></td>
<td></td>
<td></td>
<td><strong>6.6E-05</strong></td>
<td></td>
</tr>
</tbody>
</table>


Chapter 6

6. Process-based and integrated hybrid life cycle assessment of U.S. beef processing

6.1 Abstract

Hybrid life cycle assessment (LCA) incorporating process-based and economic input-output (EIO)-based inventory data has been applied in various industries (e.g., wind energy, biofuel). Yet, few hybrid LCA studies have been found in food industry. Moreover, most hybrid LCA studies focused one or two environmental categories (e.g., life cycle carbon or energy footprint), thus limiting our understanding on the other environmental categories, such as eutrophication and human toxicity. This work analyzes the life cycle environmental impacts of U.S. beef processing industry using process-based and integrated hybrid LCA. The process-based inventory includes all resource inputs and waste outputs associated with beef processing plant. The EIO-based inventory includes key activities missing in the process-based inventory, such as technical and management service, wood and paper, industrial equipment. Ten TRACI v2.1 environmental impact categories and the aggregated environmental single score are considered. The results show that environmental impacts contributed by EIO system are ozone depletion (67%), respiratory effects (42%), fossil fuel depletion (38%), smog (28%). On average, EIO accounts for 10.4% of total environmental impacts, mainly due to the embedded impacts
from industrial equipment (3.0%), technical and management services (2.7%), and wood and papers (2.1%). Furthermore, we perform uncertainty and global sensitivity analysis for all environmental categories by varying key parameters under their own distribution. The uncertainty analysis showed that the environmental single score contributed by EIO system can range from 7% to 15% under Monte Carlo simulations (10,000 runs). The global sensitivity analysis using Sobol method for all environmental categories show that the electricity, natural gas, and wastewater treatment from process and beef price from EIO system are the four most sensitivity parameters to all ten TRACI environmental categories and the environmental single score. The results suggest that pushing suppliers and service providers to become more sustainable may result in a notable improvement on certain environmental categories (i.e., ozone depletion, respiratory effects, fossil fuel depletion, smog). In order to increase the overall sustainability of beef processing, best management practice should focus on increasing energy efficiency (e.g., onsite electricity and natural gas use) and minimizing water use and improving wastewater treatment technologies to reduce nutrient emissions and heavy metal contents in sludge.

6.2 Introduction

The global meat production is expected to increase twofold by 2050 to meet the demand of increased world population and increase prosperity (Steinfeld et al., 2006). Among various meat products, beef products have been reported to have highest environmental footprints, such as greenhouse gas (GHG), water, fossil energy, eutrophication (Eshel et al., 2014; Roy et al., 2009; Ziara et al., 2016). Although many studies have shown that the majority of the environmental life cycle impacts of meat
products is in the farm stage (Asem-Hiablie et al., 2019; Mogensen et al., 2016), there is still significant room for improvements in the stage of meat processing.

With the expected growing demand for meat products, the sustainability of beef products is of increased concerns to meat processing industries and consumers. The U.S. beef is expected to play an important role in the global meat supply chain (Charles et al., 2018), advancing the sustainability of U.S. beef slaughtering is an important need. Many U.S. meat processing companies initiate sustainability programs and activities to advance the sustainability of their products (Tyson Foods, 2017). Those sustainability initiatives not only help food processing companies to take responsibility for reducing environmental footprints of their products but also helps themselves to enhance their brand images.

Life cycle assessment (LCA) is a well-established technique to quantify the overall environmental impacts of a product or system and has been widely applied in various food processing systems (Battagliese et al., 2015; Peters et al., 2010; Silva and Sanjuán, 2019). Most LCA studies of beef systems focus on beef production in the farm stage with only a few studies investigating the environmental impacts on the stage of beef processing, such as slaughtering, fabricating, and packaging. For example, Battagliese et al. (2015) measured life cycle environmental and economic impacts of U.S. beef supply chain from beef production to processing to its consumer stage using eco-efficiency analysis (EEA). However, The study from Battagliese et al. (2015) only evaluate the environmental impacts of beef processing as a whole instead of at process level as collecting data from the beef processing facilities are challenging since beef companies are generally conservative on sharing their proprietary data and granting access to collect
data onsite. Therefore, there is an important need to investigate the environmental impacts of beef processing more granularly, thus providing more useful information on the potential mitigation of environmental footprints related to beef slaughtering process.

LCA can generally be classified into three categories depending on different methods of inventory data collection, i.e., process-based, economic input-output (EIO)-based, and hybrid LCA (Crawford et al., 2018; Suh and Huppes, 2005; Yu and Wiedmann, 2018). Process-based LCA basically applies a bottom-up approach to collect inventory data of interest while the EIO-based LCA employs a top-down approach to estimate inventory data and environmental emissions from a wide range of economic activities. The process-based approach can yield more accurate inventory data than the inventory data estimated from EIO-based approach. However, process-based inventory usually results in system truncations (e.g., technical and financial services) since it is almost unlikely to collect all inventory data at the process level.

The EIO-based approach estimates inventory data at a coarser resolution, typically based on available EIO databases aggregating specific industries into a general sector. For example, specific meat processing industries (e.g., beef, pork, and lamb) are aggregated into red meat sector in the environmentally-extended input-output model of the United States (USEEIO) database developed by U.S. Environmental Protection Agency (EPA) based on IO table compiled by the US Bureau of Economic Analysis (Yang et al., 2017). The advantage of EIO-based LCA is its ability to fully capture inventory data of environmental emissions via transaction across industries, thus avoiding system truncations issues compared to traditional process-based LCA. For example, most process based LCAs do not account for the environmental impacts embedded in a wide
variety of services (e.g., financial, governmental services) when manufacturing a product due to data limitations. The hybrid LCA can be considered as a combination of process-based LCA and EIO-based LCA. It is believed that a hybrid LCA can quantify the environmental impacts more comprehensively compared to process-based and EIO-based by complementing system boundary truncation in process-based approach with EIO database. In this regards, available process-based inventory data are first used under the assumption that process-based inventory data are more accurate than EIO-based inventory data. Suh and Huppes (2005) summarized three hybrid LCA approach, including tiered hybrid, EIO-based hybrid, integrated hybrid LCA. Details of the three hybrid approaches are introduced in the section of Methods along with the application of integrated hybrid LCA in this work.

Most LCA studies on food products apply traditional process-based approaches to collect inventory data (Kim et al., 2013; Li et al., 2018a; Mogensen et al., 2016; Rotz et al., 2019). Integrated hybrid LCAs have been applied in other different systems (e.g., energy) to supplement the truncations of system boundary (Wiedmann et al., 2011; Zhao and You, 2019). However, those integrated hybrid LCAs are mainly focused on one or two environmental indicators (e.g., GHG, fossil fuel footprint), thus limiting our understanding of the wide spectrum of various environmental impacts available in LCA studies, such as eutrophication, human health, ecotoxicity.

The hypothesis of this work is that environmental impacts embedded in EIO system can be notable in certain specific environmental category compared to environmental impacts from process-based system. We first investigate the environmental impacts of U.S. beef processing at process-level using processed-based
inventory data collected from large commercial large-size beef processing facilities located in the Midwest. We then applied integrated hybrid LCA to environmental impacts of beef processing and compared with the results from process based LCA. To our knowledge, this work is the first attempt to investigate the environmental life cycle impacts U.S. beef processing industry at process-level as well as the application of hybrid LCA in the beef system. The framework developed in this work can be widely applied to many other food systems to investigate their environmental footprints and ultimately provide areas where major changes can take place.

6.3 Methodology

6.3.1 Overview of hybrid LCA approaches

Hybrid LCA has been loosely referred to any approach combining process-based and EIO-based LCA (Crawford et al., 2018). Based on different ways of inventory compilation, hybrid LCA furthered categorized into three types: 1) tiered hybrid LCA, 2) EIO-based hybrid LCA, and 3) integrated hybrid LCA. In this study, we use integrated hybrid LCA, the most comprehensive one among the three hybrid approaches.

For tiered hybrid LCA, process-based inventory includes the use and end-of-life stage and certain upstream processes while EIO-based inventory covers most upstream processes. The results are simply added as the total hybrid LCA. Tiered hybrid analysis can provide a relatively complete and quick analysis. However, since the process-based and EIO-based system are analyzed separately, the interaction between them cannot be evaluated systematically. The EIO-based hybrid analysis utilizes disaggregated industry sectors in an augmented IO table so that the inventory up to pre-consumer stage can be
calculated by EIO-based analysis and then the use and end-of-life stage can be complemented by process-based analysis. Since EIO-based approach partially utilizes the tiered hybrid approach, the process systems, and macroeconomic systems might not be fully integrated into it. The last hybrid LCA approach is the integrated hybrid LCA that systematically interconnects environmental inventory of process-based and macroeconomic systems. Assuming that process-specific data are more reliable than EIO data, the inventory of integrated hybrid LCA first utilizes process data and then the EIO data is integrated by connecting the upstream and downstream wherever process-specific data are not available. For example, in the beef processing plant, most operational resource inputs and waste outputs are part of the process-specific data. However, the environmental impacts embedded with construction, operation maintenance, and services in a beef processing plant and other processes for manufacturing materials are not readily available through process-specific data and can be linked via the upstream and downstream cutoff matrix, instead of being treated independently in tiered hybrid LCA.

6.3.2 System boundary of beef processing in the U.S.

As shown in Figure 6.1, the system boundary of beef processing considered in this study consists of two systems: a process-based system and EIO-based system. The process-based part includes typical steps in beef processing facilities and its onsite and offsite waste treatment. A typical beef processing facility generally starts from the holding yard, killing floor, chilling room, fabrication floor, and finally various products are packaged and stored. The killing floor can further be split into key steps, including stunning, bleeding, hide and head removal, sequential antimicrobial interventions, rendering. A wide range of beef products and byproducts can be produced from a beef
processing plant. Since the focus of this study is the functionality of processing beef, rather than various beef products, we chose the functional unit to be processing 1000 kg of live-cattle weight (1000 kg LCW). The EIO-based system includes the upstream cutoff systems usually excludes in the process-based system. For example, the construction, equipment maintenance, and various services of beef processing plants are not included in the process-based system due to the data limitations. The details on integrating EIO-based and process-based systems can be found in the section of life cycle inventory analysis.

Figure 6.1 System boundary and methodology framework
6.3.3 Life cycle inventory analysis

The process-specific data (e.g., resource inputs and waste outputs in Figure 6.1) are collected from the two commercial U.S. beef processing plants located in Midwest (Li et al., 2019). Those data are further normalized based on the functional unit (1000 kg of live-cattle weight) and processed as the technology matrix coefficient for the process-based system. According to Suh and Huppes (2005), the general mathematical formula of integrated hybrid LCA can be expressed in Eq. (6-1):

\[
E = [E_P \ E_{IO}] \begin{bmatrix} A_P & -C_d \\ -C_u & 1 - A_{IO} \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \end{bmatrix}
\]

(6-1)

Where E is the total environmental impact vector from both process-based and EIO-based inventory. \( E_P \) denotes the coefficient matrix of direct environmental emissions per physical units (e.g., kg CO\(_2\) emissions per kWh of electricity) from process-based inventory. \( E_{IO} \) represents coefficient matrix for direct environmental emissions per monetary unit (e.g., kg CO\(_2\) emissions producing one-dollar value of a commodity) from EIO system. \( A_P \) symbolizes the technology coefficient matrix (e.g., physical amount of kWh per functional unit of beef processing) for physical flows in process systems. \( A_{IO} \) is the direct requirements matrix (e.g., monetary value of financial service sectors to one-dollar of meat) constructed in USEEIO dataset using 2007 input-output table derived from the US Bureau of Economic Analysis. \( -C_u \) is the upstream cut-off flows (e.g., monetary value of financial service sectors to the beef processing process) with a negative sign representing flow direction from EIO system to process system while \( -C_d \) is the downstream cut-off flows (e.g., the amount of beef processing products to one-dollar of financial service sectors) with a negative sign representing flow direction from
process system to EIO system. The flow direction of $-C_u$ and $-C_d$ can also been seen in Figure 6.2. $C_u$ and $A_{1O}$ are given in monetary units while the physical flow matrix $T$ and $C_d$ are shown in physical units. $[Y]$ is the demand vector containing the product based on functional unit (e.g., 1000 kg LW beef) that will be supplied to outside of the system.

![Diagram of integrated hybrid LCA model for beef processing](image.png)

The unit environmental impacts (i.e., $E_P$ and $E_{1O}$) of process-based (e.g., kg CO$_2$/kWh electricity) can be obtained from Ecoinvent v3.3 ([https://www.ecoinvent.org/](https://www.ecoinvent.org/)) and EIO-based inventory (e.g., CO$_2$/$/ commodity) can be obtained from USEEIO (Yang et al., 2017). The technology coefficient matrix of $A_P$ was obtained via process-specific data in two commercial beef processing in the US Midwestern. The technology coefficient matrix of $A_{1O}$ was obtained from USEEIO dataset developed by U.S. EPA. The downstream cutoff matrix $C_d$, is assumed as zero, since the economic scale of the system for beef processing is negligible compared to the EIO system for the U.S.
In order to construct the upstream matrix $C_u$ that represents inputs from EIO system to the process-based system, five steps in the literature were followed (Wiedmann et al., 2011). First, a concordance matrix matching Ecoinvent processes and EIO sectors was created with 388 rows representing U.S. economic sectors and 14 columns representing processes associated with beef processing. The cells in the concordance matrix are populated with ones if economic sectors and processes are matched and other cells are zeros. Second, a matrix containing unit prices of processes were established from Ecoinvent v3.3 and various publicly available sources and converted from purchaser prices to basic prices in the US currency in 2013 to be consistent with the currency in USEEIO dataset. The conversion ratios of purchaser prices to basic prices of different products were retrieved from the Comprehensive Environmental Data Archive academic version, a peer-reviewed EEIO dataset for potential applications in LCA studies (Suh, 2016). The inflation factors of basic prices at different years are accounted for using average annual producer price indices (PPI) from Federal Reserve Economic Data (https://fred.stlouisfed.org/). The USEEIO was developed based on the IO tables compiled by the US Bureau of Economic Analysis (https://www.bea.gov/) to represent direct requirement commodity input in rows by commodity output in columns. Third, the technical coefficient matrix was directly populated with coefficient from USEEIO in the concordance matrix from the first step. Specifically, the technical coefficients $a_{ij}$ from USEEIO are populated into cells $C_{ik}$ of the concordance matrix where $i$ is an EIO sector and $j$ is the economic sector matching the project $k$. Fourth, the matrix from the third step is element-wise multipled by unit price matrix from the fourth step to produce a price-
weighted coefficient matrix. The final step is to check and delete the upstream inputs in
the matrix $C_u$ already covered in process system as the physical units.

### 6.3.4 Impact assessment method

Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI v2.1) was used as the environmental impact assessment method (Bare, 2012). TRACI v2.1 was developed by the U.S. EPA to provide characterization factors for ten impact categories, including ozone depletion, global warming, smog formation, acidification, eutrophication, carcinogen, non-carcinogen, respiratory effects, ecotoxicity, fossil fuel depletion (Figure 6.3). The USEEIO has also provided the readily inventory and characterization factors of TRACI v2.1 environmental categories, which allows harmonizing the process-based and EIO-based environmental impacts together. The ten environmental categories were normalized using the environmental baseline impact per capita in the U.S. in 2008 (Ryberg et al., 2014). Finally, all environmental categories were weighted using a set of factors recommended by Sustainable Mind methodology given the preference of each environmental category (Meijer, 2013).

Figure 6.3 Impact assessment method, normalization, and weighting in this study
6.3.5 Uncertainty and sensitivity analysis

Various sources of uncertainties and assumptions exist for hybrid LCA studies, such as input data uncertainty (e.g., process-specific data, prices) and model uncertainty (e.g., inventory substances, characterization factors). We conducted a Monte Carlo uncertainty analysis to demonstrate the probability distribution of environmental categories under the propagation of various uncertainty sources. In this study, four uncertainty sources are considered, including $A_P$, $E_p$, $C_u$, $E_{IO}$ in the hybrid LCA matrix. Due to the limited data, no distribution information is available of the four uncertainty sources. Therefore, assumptions are made to describe parametric probability distributions of those four uncertainty sources based on available data and literature. For $A_P$, triangular distribution with 70%, 130% of process-specific data (e.g., m$^3$/1000kg LCW, kWh/1000 kg LCW) was assigned as the lower and upper limit, respectively, based on the coefficients of variation in onsite data via one-year data collection (Li et al., 2018b). For uncertainty in $E_p$, it is assumed to follow a lognormal distribution with 10% of standard deviation. For uncertainty in $C_u$, it is assumed to follow triangular distribution with 50%, 150% of unit prices being the lower and upper limit. For uncertainty in $E_{IO}$, the pedigree matrix provided by USEEIO assessing the data quality of the $E_{IO}$ is used to construct its uncertainty distribution.

To investigate the impacts of input parameters on the final results, we also perform global sensitivity analysis using Sobol method to evaluate the impacts on outputs by changing the input parameters, including the amount of onsite energy usage (i.e., natural gas and electricity) and product price, to demonstrate the actual range of results.
can change, while keeping other parameters follow their corresponding intrinsic distribution (Groen et al., 2017). The Sobol indices decompose variance of outputs into orthogonal terms independent to each other. The Sobol’s main effect (SME) index calculates main variance contributed by the first order term of parameters while the Sobol’s total effect (STE) index calculates total variance explained by the parameters, including interactions among parameters. In the case of the linearity of the integrated hybrid LCA model in this study, the SME index is approximately to the STE index since all interaction terms between variables are approximately zero. Detailed steps and sampling algorithms implementing the Sobol method to the LCA model can be found in the work of Groen et al. (2017). The uncertainty and sensitivity analysis were conducted in Python and the codes are accessible from the authors upon request.

### 6.4 Results and discussion

#### 6.4.1 Process-based LCA

The contribution of various processes during beef processing to the various environmental life cycle impacts are shown in Figure 6.4. The x-axis shows the ten TRACI environmental categories and left y-axis presents specific process contribution by percentage and right y-axis is the normalized value of each environmental category. The normalized values of various environmental categories are calculated by the ratio of the environmental burdens of each environmental category to the total environmental burden shared by one American in the year of 2008 (Ryberg et al., 2014).

The overall global warming for processing 1000 kg live-cattle weight (LCW) at plant is estimated at 250 kg CO\(_2\)-eq (Table 6.1). Asem-Hiablie et al. (2019) conducted a
detailed LCA study on the US beef supply chain from cradle to farm gate to post-farm gate and chose 1 kg of consumed and boneless beef as function unit, which is equivalent to 3.45 kg live weight. After converting the results from that study to the same functional unit (i.e., 1000 kg LCW) selected in this study, 237 kg CO$_2$-eq/1000 kg LCW was reported for the sectors of packaging and case-ready, which is similar to the system boundary of this study based on the description of those two sectors in the original paper (Rotz et al., 2019). However, it is worth noting that the processing and packing stage only accounts 1.7% of the whole beef supply chain. Another study focused on environmental impact of beef production in Mexico also concluded that about 255 kg CO$_2$-eq/1000 kg LCW was produced during beef processing stage of intensive system where beef cattle are raised in feedlot (Huerta et al., 2016). Electricity and natural gas use contribute to the most of global warming due to CO$_2$ and CH$_4$ from fossil fuel (Figure 6.4).

The result of the acidification impact in this work is 0.86 kg SO$_2$-eq/1000 kg LCW while the reported value from Rotz et al. (2019) is 1.25 kg SO$_2$-eq/1000 kg LCW on the same functional unit, which is considered to be close given the fact that numerous substances involved for calculation. Electricity also contributes to the most of ecotoxicity due to copper and zinc emissions to water. 80% of carcinogen impact is caused by the emissions of chromium VI to water from the production of chemicals, natural gas and electricity. The process of wastewater treatment contributes most of eutrophication (56%) due to nutrient emissions (i.e., BOD, ammonia, phosphorus) and non-carcinogen (58%) due to heavy metals emitted to agricultural soil when applying sludge on the farmland.
Contribution of specific processes to environmental life cycle impacts of the US beef processing

Carcinogen and ecotoxicity are the two major impacts when scaling to the average impacts per capita in the US, each accounting around 0.058. This means that the environmental impacts of ecotoxicity and carcinogen due to processing 1000 kg LCW is equivalent to 5.8% of ecotoxicity and carcinogen impacts shared by one American in the year of 2008. The similar interpretation applies to other environmental categories. The non-carcinogen impact of processing 1000 kg LWC is around 4.0%, eutrophication 2.1%, and fossil fuel depletion 2.5%. Other remaining environmental impacts are all under 1%. Note that U.S. beef consumption per capita is 35.9 kg carcass weight in 2016, equivalent to 57.7 kg live cattle weight assuming 62% of live cattle can be produced as carcass.
(USDA ERS, 2018). The coefficient of 0.0577 (57.7 kg/1000 kg) should be further multiplied to evaluate the contrition of environmental impacts of beef processing due to the same amount of beef per U.S. capita. For example, 0.33% of ecotoxicity and carcinogen impacts shared by one American is due to the beef processing. Although normalized values are useful for relative comparison, the environmental impacts shared by one American are from 2008 while the primary data of beef processing plants are collected from 2016.

Table 6.1 Environmental impacts of U.S. beef processing for 1000 kg LCW

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Process-based system</th>
<th>EIO systems</th>
<th>Total</th>
<th>Normalized value (dimensionless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>4.99E-06</td>
<td>6.9E-06</td>
<td>1.2E-05</td>
<td>7.37E-05</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM2.5 eq</td>
<td>4.18E-02</td>
<td>1.8E-02</td>
<td>5.9E-02</td>
<td>2.45E-03</td>
</tr>
<tr>
<td>Smog</td>
<td>kg O3 eq</td>
<td>7.39E+00</td>
<td>1.8E+00</td>
<td>9.2E+00</td>
<td>6.61E-03</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>2.17E+02</td>
<td>3.5E+01</td>
<td>2.5E+02</td>
<td>1.04E-02</td>
</tr>
<tr>
<td>Fossil fuel depletion</td>
<td>MJ surplus</td>
<td>3.10E+02</td>
<td>1.1E+02</td>
<td>4.2E+02</td>
<td>2.25E-02</td>
</tr>
<tr>
<td>Acidification</td>
<td>kg SO2 eq</td>
<td>7.53E-01</td>
<td>1.0E-01</td>
<td>8.6E-01</td>
<td>9.41E-03</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>4.13E-01</td>
<td>3.3E-02</td>
<td>4.5E-01</td>
<td>2.06E-02</td>
</tr>
<tr>
<td>Non-carcinogen</td>
<td>CTUh</td>
<td>4.16E-05</td>
<td>3.2E-08</td>
<td>4.2E-05</td>
<td>3.96E-02</td>
</tr>
<tr>
<td>Carcinogen</td>
<td>CTUh</td>
<td>3.03E-06</td>
<td>6.5E-09</td>
<td>3.0E-06</td>
<td>5.75E-02</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>CTUe</td>
<td>6.45E+02</td>
<td>2.3E+00</td>
<td>6.5E+02</td>
<td>5.85E-02</td>
</tr>
</tbody>
</table>

6.4.2 Integrated hybrid LCA

The results of the integrated hybrid LCA across ten TRACI environmental categories are presented in Figure 6.5. The impacts of ecotoxicity, carcinogen and non-carcinogen are all from accounted from the process-based system. The impacts of eutrophication, acidification, and global warming are also almost contributed by the process-based system (>80%). The major environmental impacts contributed by the EIO
system are ozone depletion (67%), respiratory effects (42%), fossil fuel depletion (38%), and smog (28%), mainly due to the environmental impacts from the sectors of wood and papers, industrial equipment, and technical and management services. This implies that pushing suppliers and service providers to become more sustainable may result in a notable improvement on these categories.

Figure 6.5 Integrated hybrid LCA midpoint results of the US beef processing

The environmental single score of the hybrid LCA during the US beef processing with the bar of pie demonstrating the breakdown of environmental single score from various economic sectors in the EIO system is shown in Figure 6.6. As can be seen in Figure 6.6, most of the environmental single score is accounted in the process-based system (89.6%) while 10.4% of environmental single score comes from the EIO system. This is because that most environmental single score is caused by key process-based inventory, such as natural gas and electricity use. Within the EIO-based system (10.4%), the industrial equipment sector is the biggest contributor (3.0%), followed by technical
and management services (2.7%) and wood and papers (2.1%). Other remaining sectors account 2.6% in total.

Figure 6.6 Integrated hybrid LCA environmental single score of the US beef processing

6.4.3 Uncertainty and sensitivity analysis

In Figure 6.7, the probability distributions of ten TRACI environmental categories and on the far right, the percentage contribution of EIO system to the overall single score are shown in the violin plot while the median and quartile values are displayed in box plot inside the violin. The thickness of the violin shape represent the frequency of sample points. Note that the units in x-axis are displayed in their corresponding physical units of each environmental category so that the y-axis positions of different categories cannot be
compared. The results show that all environmental categories follow the bell-shape curve. The categories of ozone depletion, ecotoxicity and single score by EIO have a flatter and wider bell-shaped curve because they are involved with more uncertainty sources. The overall contribution of EIO system ranges from 7% - 15% under uncertainty.

Figure 6.7 Violin plot of environmental categories representing the sampling distribution from Monte Carlo simulation (10,000 runs).

In order to further evaluate the impacts of key variables on the results of each environmental category, global sensitivity analysis (GSA) was conducted on ten TRACI impact categories and the aggregated environmental single score as shown in Figure 6.8. The sensitivity index in y axis represents how much key parameters explains of the output variance. For example, 0.95 of sensitivity index for beef ($) on ozone depletion
means that 95% variance of ozone depletion is from the beef ($). For brevity, the parameters that their sensitivity indexes are than 2% was grouped as “others”.

The key parameters considered for the GAS includes the process-based foreground data (e.g., the physical amount of electricity, natural gas, chemicals, packaging materials) that are directly linked to the processes during the beef processing and the prices of those foreground data. In Figure 6.8, each subplot (A to J) represents the results of GSA on one environmental indicator from TRACI impact categories while Figure 6.8 (K) represents the GSA on the aggregated single score. The beef price ($) has dominant sensitivity impact (explaining > 50% of total output variance) in the categories of ozone depletion (95%), smog (60%), respiratory effects (80%), and fossil fuel depletion (60%), and notable impact (explaining between 20 and 50%) in the categories of global warming (37%), acidification (31%). The physical amount of electricity has dominant sensitivity impact on acidification (58%) and ecotoxicity (83%) and notable impact on smog (30%) and carcinogen (16%). The physical amount of the natural gas has notable impacts of global warming (41%) and fossil fuel depletion (34%). Overall, the aggregated single score is mostly impacted by the four key parameters: 1) amount of electricity usage (32%), 2) amount of natural gas usage (20%), 3) beef price (20%), and 4) wastewater treatment (12%).
Figure 6.8 Contribution to output variance for Sobol’s total sensitivity index of the selected inventory parameters (i.e., usage and prices).

6.5 Conclusions

To our knowledge, this work is the first analysis to apply integrated hybrid LCA in the food processing industry. The integrated hybrid LCA complements the system boundary of process-based LCA and can better quantify the environmental impacts for
the beef processing plants in the US. We applied USEEIO database for the inventory from EIO system, which allows us to consider all ten TRACI environmental categories. We further normalize and weight the ten categories into the environmental single score. Monte Carlo simulations were performed to simulate the distributions of all TRACI categories as well as the single score contributed by EIO systems. The global sensitivity analysis considers the uncertainty distribution of all resource usage rate and their prices and identified electricity, natural gas, and wastewater treatment from process and beef price from EIO system explain most variance of all ten TRACI environmental categories and the environmental single score. Selecting suppliers and service providers with more sustainable practices may result in a notable improvement on certain environmental categories (i.e., ozone depletion, respiratory effects, fossil fuel depletion, smog). Best management practice should focus on increasing energy and water efficiency (e.g., onsite electricity, natural gas, water use) and minimizing nutrient emissions and heavy metal contents in sludge. The hybrid LCA framework applied in this study can be easily adapted to other food industry to enhance our understanding of embedded environmental impacts from EIO systems.
Chapter 7

7. Conclusions and Proposed Future Research

7.1 Conclusions

In this dissertation, assessments of U.S. beef processing industry using different approaches were conducted to advance our understanding of the sustainability of the U.S. beef processing industry. This dissertation strives to fill the four specific knowledge gaps: 1) scarce process-level data gap on beef processing facilities; 2) absent comprehensive sustainability assessments, to help avoid sustainability shifting, for antimicrobial systems within beef processing facilities; 3) unknown tradeoffs of human health among environmental and occupational impacts caused by the U.S. beef processing industry and foodborne illness caused by beef consumption. 4) system truncations of process-based LCA of the beef processing industry due to the missing cutoff systems.

To fill the data gap, a detailed assessment of water and energy use at the process level was first conducted to enhance the understanding of the food-energy-water nexus in the beef processing industry. The kill floor and plant cleaning are the primary water uses while the refrigeration compressor system is the largest use of electricity, consuming 24.5% of plant-wide electricity. A regression analysis using daily data through one-year period suggests that if the average local temperatures increase by 2.5°C, the current plant
will use 0.5% more water but 5% less thermal energy and 1% less electricity when operating at the same operating capacity. Engineers can apply this case study as an example to share with their clients seeking to collect and analyze data with the goal of identifying water and energy conservation approaches.

To address the absence of life cycle sustainability assessment models of antimicrobial systems in beef processing, three commercial antimicrobial systems were first evaluated from the environmental and economic perspectives. The results show that chemicals, natural gas, and wastewater dominate all environmental impact indicators. Systems featured with chemicals contributes mostly to ecotoxicity, eutrophication, and human health impacts while systems featured with thermal pasteurization leads to the majority of global warming and energy depletion.

A more comprehensive assessment framework was developed to advance the sustainability knowledge on sustainable food safety through the arrangement of sequential antimicrobial systems in the U.S. beef processing industry. The work serves as the first analysis jointly evaluating effectiveness, environmental impacts, economic costs of antimicrobial systems of U.S. beef processing industry was via an integrated life cycle assessment framework. The evaluation identifies that the use of steam in antimicrobial systems results in the best combination of low cost and environmental impact, and high microbial reduction. Devalued meat due to discoloration has considerable environmental and economic impacts. Steam pasteurization as the main treatment is required for achieving 4.5 log CFU/cm² reduction or higher. Three systems using hot water or/and peracetic acid spray in the pre-evisceration wash or/and carcass wash and steam
pasteurization as the main treatment result in low environmental and economic impact, and high microbial reduction.

The U.S. beef processors have been striving to provide safe and high-quality beef. This requires intensive resource consumption and causes occupational hazards during slaughtering. To understand the impacts of foodborne illnesses of beef consumption, environmental pollution and occupational hazards of beef slaughtering on human health, a methodology was introduced that can help advance the sustainability knowledge about the human health tradeoffs. The three impacts are of a similar magnitude. The results suggest that new food safety innovations to reduce foodborne pathogen should be considered jointly with environmental impacts and occupational hazards to prevent impact shifting. This study has particular relevance as consumers and the beef slaughtering industry are focused on sustainability in addition to employee and beef microbiological safety.

To address the deficit of cutoff systems in process-based LCA, an integrated hybrid LCA was constructed to systematically interconnect the cutoff systems with the process-based systems using USEEIO as macroeconomic systems and ecoinvent as the process-based system. The results show that the economic systems (e.g., services) can have considerable embedded environmental impacts, especially in the environmental categories of ozone depletion (67%), respiratory effect (42%) and fossil fuel depletion (38%). The global sensitivity analysis using Sobol method further identifies the electricity, natural gas, wastewater treatment from process-based LCA and the beef price from economic system are the four most sensitive parameters. Overall, the economic
systems contribute to 7 to 15% of aggregated environmental single score under uncertainty (10,000 Monte Carlo runs).

7.2 Proposed future research

Although multifaceted assessments for the sustainable development of beef processing were evaluated in this dissertation, new hypothesis for future research can be explored to further address the challenges and barriers of the sustainable development of the beef processing industry and extended to other meat processing industry. Following areas worth further investigations:

- This dissertation collected inventory data from two commercial beef processing facilities in Midwestern. More process-level data considering the variations of seasonal changes and spatial locations of beef processing industry need to be collected to expand the database, such as water, energy, materials inventory, and waste outputs at process-level. The data should be collected with the goal to construct time-series models and agent-based models for key processes (e.g., antimicrobial processes) where mathematical optimization algorithm can be further applied to achieve Pareto optimal front for multiple objectives (e.g., food safety, water, energy, life cycle GHGs).

- The economic assessment performed for antimicrobial systems in this dissertation includes operational costs and downstream wastewater treatment and hidden product loss of devalued meat. Yet, the non-market cost in life cycle costs, including the social cost of carbon and cost of ecotoxicity and human health, have not been incorporated due to data limitations. The U.S. EPA and other federal
agencies estimate the social cost of carbon in the dollar to represent the long-term damage done by carbon dioxide as well as the benefits of carbon dioxide reduction. However, the social cost of other environmental impacts has not been well quantified due to methodological and data limitations.

- Other antimicrobial interventions considered promising include ionizing radiation, ozone, and other different antimicrobial chemicals and BoviBrom [(1,3-Dibromo-5,5-dimethyl hydantoin)] are encouraged to be incorporated into the assessment framework of antimicrobial systems. Systematic review and meta-analysis are required to evaluate the effectiveness of antimicrobial interventions especially applications of peracetic acid and other popular antimicrobial chemicals to improve the quality of microbial load reduction estimates.

- The dataset of economic systems used in hybrid LCA is USEEIO, which represents the requirement relationship among domestic US economic sectors. In reality, however, the economy is connected globally nowadays. Therefore, a global, detailed multi-regional input-output database is necessary, such as exiobase ([https://exiobase.eu/](https://exiobase.eu/)). Yet, such an existing database does not have readily available environmental categories consistent with TRACI v2.1. Further data processing to connect the inventory data with the characterization factors might be required.

- The methodologies and frameworks of integrated assessments of antimicrobial systems and human health comparison have promising implications in advancing sustainable development other meat processing industry (e.g., poultry and pork
processing industry) and even more general food processing industry as food safety and environmental and economic sustainability are universal concerns for them.
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Bureau of Labor Statistics, Injuries, Illnesses, and F., 2015c. TABLE R67. Number and percent distribution of nonfatal occupational injuries and illnesses involving days away from work by nature of injury or illness and number of days away from work, and median number of days away from work, private industry.

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