Food waste generation at households and the resulting life cycle environmental impacts: A case study of fresh and frozen broccoli

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public

Statement of Contributions

Chapter 2 of the thesis contains material from accepted manuscript by the Journal of Cleaner Production (https://www.journals.elsevier.com/journal-of-cleaner-production).

Sohani Withanage is the lead author who drafted the manuscript under the direct supervision of the co-authors Goretty Dias and Komal Habib. Each co-author provided valuable intellectual input in the manuscript drafts. The citation for the publication is provided below.

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Abstract

Food waste has serious environmental and economic consequences, making it a global issue with growing attention from academia, industry and policy makers. The key to reduction or better management of food waste is understanding the quantities and composition of food waste at each stage of the food supply chain. In developed countries, it is reported that the highest percentage of food loss/waste happens in the post-consumption stage, especially at households. Understanding the composition of avoidable food waste at households is important to assess the applicability of food preservation techniques, such as freezing, to reduce the life-cycle environmental impacts of the food system. Thus, the current study aims to understand the impacts of food waste across the supply chain, by comparing the life-cycle environmental impacts of fresh and frozen produce, using broccoli as a case study vegetable. This aim was achieved in two stages. First, 16 samples of green bin waste generated at households in the Region of Waterloo were analyzed to understand the composition of the avoidable food waste fraction. The findings suggest that 43% of all food waste is avoidable and 86% of avoidable food waste is plant-based, indicating that fresh fruits and vegetables are the most frequently wasted food item in households. Since frozen vegetables are known to generate comparatively less food waste than their fresh counterparts due to increased shelf life and ability to utilize ‘ugly’ produce, it is important to understand the life-cycle environmental impacts of fresh and frozen produce, taking into account how waste occurs in each supply chain. Broccoli was selected as the case study vegetable and a comparative life cycle assessment (LCA) was carried out to analyze the life-cycle environmental performance of fresh and frozen broccoli produced and consumed in Ontario. Findings suggest that within the study context, fresh broccoli performs better in four impact categories; acidification, global warming, ozone depletion and resource depletion, whereas frozen broccoli performs better in eutrophication. Therefore, the reduced FW that occurs in frozen broccoli supply chains is not sufficient to offset the environmental impacts of energy use for additional processing and frozen storage. However, the need for more rigorous research is emphasized for better understanding of the fresh and frozen supply chains, and how to minimize impacts from associated food waste.

Keywords: food waste, avoidable, composition, households, Life Cycle Assessment, broccoli.

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Dedication

To my father, who taught me to dream and to dream big, but could not stay long enough to see me painting those dreams one stroke at a time.

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List of Abbreviations

AP	Acidification Potential
CEC	Commission for Environmental Corporation
EP	Eutrophication Potential
FAO	Food and Agriculture Organization
FL	Food Loss
FLW	Food Loss and Waste
FSC	Food Supply Chain
FW	Food Waste
GHG	Greenhouse gases
GWP	Global Warming Potential
LCA	Life Cycle Assessment
ODP	Ozone Depletion Potential
RDP	Resource Depletion Potential
UK	United Kingdom
US	United States

CHAPTER 1

Introduction

The global population has doubled during the last half century resulting in a dramatic increase in global food demand and production. With the population continuing to grow further, it is estimated that the global demand for food will keep escalating for at least another 40 years (Godfray et al., 2010). Although feeding 9.8 billion people by 2050 itself is a challenge, what is far more challenging is doing it in a way that does not induce more environmental damage or compromise ecosystems. To overcome this challenge, drastic alterations are needed in the way food is being produced, processed, stored, distributed and consumed (Eriksson, 2015). According to Godfrey et al. (2010), there are five strategies that could help in meeting these challenges, namely: closing the yield gap, increasing production limits, expanding aquaculture, changing dietary patterns, and reducing waste. While all these strategies focus on utilizing the full potential of the production system, reducing waste is unique as it focusses on food that has already been produced, but not consumed due to various reasons (Ericksen, 2008).

Food loss and waste that occurs throughout the food supply chain (FSC) has recently received increasing attention from the media, researchers, politicians, companies and the general public due to its adverse impacts on economy, society and most importantly, the environment. Food waste (FW) carries a significant economic burden, not only due to the associated monetary value of the lost food that was intended to be consumed, but also due to the cost of disposal (FAO, 2014b). The estimated annual financial loss due to food loss and waste (FLW) in the United States (US) alone is estimated to be $1.3 billion (Buzby & Hyman, 2012). In the United

Kingdom (UK), financial losses due to wasted food per household range from $566 to $593 annually (Secondi et al., 2015). The total monetary value of avoidable FW alone in Canada was $49.5 billion in 2016, which was equal to 3% of the country's Gross Domestic Production for that year (Gooch & Nikkel, 2019). This evidence implies that significant financial losses can be avoided by systematically reducing FW.

Social impacts related to FW are rather complex as it is associated with the moral implications of food security. Since food security is deeply connected to global economy and food distribution, finishing off food in one's plate will not make a starving person any happier (Eriksson, 2015). Throwing away millions of tons of food, while one in every seven persons in the world is still suffering from malnourishment, is more of a moral implication than a direct cause-effect relationship (Godfray et al., 2010). However, reducing FW has an indirect influence due to reduced demand for the finite resources needed for food production (Eriksson, 2015).

Environmental impacts associated with FW range across a number of concerns including water use, energy use, land use, biodiversity loss and carbon emissions (FAO, 2013; Godfray et al., 2010). Especially when edible food items are wasted, it is not just the food that is wasted, but all the resources that were consumed from agricultural production until final consumption are wasted along with the food. The Food and Agriculture Organization (FAO) reported that if FW were a country, it would be the third largest emitter of greenhouse gases (GHG) after the USA and China, with an annual carbon footprint of 4.4 gigatons (10^9 tons) (FAO, 2014b). Moreover, it is also estimated that 28% of the world's agricultural land is used to produce food that is ultimately lost or wasted every year (FAO, 2013). With the growing competition on land, water and energy, in addition to the challenges posed by climate change, reducing FLW along the FSC is an urgent requirement that will ultimately reduce the overall impacts of the food system on the environment.

As a result of recent studies that have highlighted FLW impacts, reducing FLW has emerged as a priority on a number of global and national political agendas. The Sustainable Development Goals, recently released by the United Nations, has a target to reduce the global per capita FW generation at retail and consumer levels by 50% by 2030 (United Nations, 2015). Consequently, both the USA and the European Union have also adopted this target; additionally, the African Union has included a commitment to halve post-harvest food losses by 2015, in the 2014 Malabo Declaration (Xue et al., 2017).

Knowledge and methodological gaps in quantifying FW generation have been identified as the major obstacles in addressing the FW generation issues by several researchers, as it is difficult to target, prioritize, and design actions to prevent and reduce FLW without the knowledge of exact composition and the quantities generated (Chaboud, 2017; Edjabou et al., 2016; Eriksson et al., 2012; Parizeau et al., 2015). Thus, quantification and characterization of FLW at the local level and at each stage of the food supply chain is considered to be a crucial step in FLW reduction.

Household level quantification and characterization of FW have been done by several researchers in Denmark (Edjabou et al., 2016, 2018), Finland (Silvennoinen et al., 2014), China

(Song et al., 2018), Japan (Munesue & Masui, 2019), Lebanon (Mattar et al., 2018), and Norway (Hanssen et al., 2016) including many other countries. The majority of FW studies at household level (e.g. Abdelradi, 2018; Filipová et al., 2017; Mattar et al., 2018; Nikolaus et al., 2018; Parizeau et al., 2015; Richter, 2017; von Kameke & Fischer, 2018) focus on understanding the perceptions, attitudes, and beliefs of consumers that lead to FW generation using household surveys, interviews and FW diaries. While most of these studies rely on rough estimates for FW quantities generated from self-reported data, secondary sources and national-level, loss-adjusted waste estimates, only some studies (e.g. Delley & Brunner, 2017; Edjabou et al., 2016, 2018; Elimelech et al., 2018; Parizeau et al., 2015; von Massow et al., 2019) have attempted to measure FW directly. These studies highlight the need to characterize household level FW according to their composition instead of merely quantifying, as only a composition analysis can reveal the fraction of avoidable FW. Understanding and quantifying the avoidable fraction is crucial for developing measures and strategies for source reduction (CEC, 2019; Edjabou et al., 2016; von Massow et al., 2019).

Many previous studies have reported that fresh fruits and vegetables are the largest contributors to avoidable FW at households (Edjabou et al., 2016; von Massow et al., 2019; WRAP, 2009). Perishability of fresh produce when coupled with inefficient meal planning and storage can result in higher amounts of FW that could have been avoided (Martindale, 2014). Similarly, fresh produce plays a major role in FW during food processing and retail stages of the FSC too, due to expectations of cosmetic perfection. In many instances, ‘ugly produce’ that does not meet marketable size, colour, or shape, gets wasted along the FSC, although they are perfectly edible and nutritious (Gunders, 2012).

Preserving perishables by freezing has been identified as a plausible alternative to increase shelf-life and decrease waste, which has recently acquired some attention in FW debates. Frozen fruits and vegetables are reported to generate significantly less FW along the life-cycle due to the increased shelf-life and also the ability to utilize 'ugly' or otherwise unmarketable produce (Janssen et al., 2017; Martindale & Schiebel, 2017). However, it should not be ignored that frozen fruits and vegetables consume comparatively higher amount of energy for processing, storage and distribution, as well as higher amounts of plastic packaging in some instances compared to fresh produce (Canals et al., 2008; Chapa et al., 2019). Thus, it is of timely importance to understand the life-cycle environmental impacts of fresh and frozen produce accounting for the FW along the FSC.

1.1 Research objectives and the structure of the thesis

The overall aim of this thesis is to provide new information on the composition of FW in the households of the Region of Waterloo, Ontario, and to compare the life-cycle environmental impacts of fresh and frozen produce in order to understand if reduced FW in cold chains outweigh the additional energy use. This aim was achieved in three steps, namely: (a) a systematic literature review to understand the household FW quantification and composition analysis methods; (b) an audit of food waste generated at the household in the Region of Waterloo, and (c) a comparative life cycle assessment (LCA) of fresh and frozen produce using broccoli as a case study. Specific research objectives for each of the steps are as follows,

Literature review:

I. To compare household FW quantification and composition analysis methods to present a critical overview of strengths and limitations of each method

Household FW audit in the Region of Waterloo:

II. To understand the average composition of FW generated at the household of the Region of Waterloo by quantifying the avoidable fraction

III. To identify the categories of food that contributes mostly to the avoidable fraction of household FW

LCA of fresh and frozen produce; a case study of broccoli:

IV. To compare the life-cycle environmental impacts of fresh and frozen broccoli produced and consumed in Ontario to understand whether the avoided FW in frozen broccoli is sufficient to offset the impacts due to freezing

The next three chapters of the thesis are dedicated to each of the above three objectives of the research, and are presented in the format of stand-alone articles. Chapter 2 presents the systematic literature review in the format of a stand-alone article that was accepted for publication in the Journal of Cleaner Production. Chapter 3 is dedicated to the audit of FW generated at the household, and Chapter 4 presents the LCA of fresh and frozen broccoli. The final chapter of the thesis discusses the overall contribution of the research and its limitations providing directions for future research.

CHAPTER 2

Review of household food waste quantification methods: focus on composition analysis

Food loss and waste has become an increasingly discussed topic in recent years due to the associated economic and environmental burden. Knowledge and methodological gaps in quantifying food waste generation have been identified as the major obstacles in addressing the food waste generation issues by several researchers. Lack of standard methodology in quantifying food waste at households had led researchers to employ numerous methods that would generate incomparable results. Considering the absence of a critical and comprehensive review of food waste quantification methods, the current study aims at presenting a thorough literature review to compare household food waste quantification methods with special focus on methods addressing composition analysis. In this review, a total of 45 studies considering four main food waste quantification methods, namely surveys, kitchen diaries, waste audits and estimates based on secondary data are reviewed in detail to compare the strengths and limitations of each method. The need for standardized methodologies for household food waste quantification is further emphasized.

2.1 Introduction

The current global population of 7 billion is estimated to reach 9.8 billion people by the year 2050 (Godfray et al., 2010). With the increasing population, the global demand for food will also escalate, imposing an inherent pressure on the global food supply system (Godfray et al., 2010). The Food and Agriculture Organization (FAO) has estimated that globally, 1.3 billion tonnes of food is being lost or wasted every year with an associated cost of 750 billion US dollars (FAO, 2015). In Canada, it is estimated that 58% of total food production gets lost or wasted every year throughout the food supply chain. The monetary value of avoidable food loss and waste alone is $49.5 billion in 2016, which is equal to 3% of the country's gross domestic production (Gooch & Nikkel, 2019). Due to the extent of food that is being wasted annually across the world, and the associated enormous environmental and socio-economic burden of this FW, authorities are prioritizing a progressive reduction of FW generation (Abdulla et al., 2013). Quantifying the amounts of FW generated and analyzing its composition are considered crucial steps in reducing FW generation at each stage of the food supply chain (Xue et al., 2017). A major obstacle to quantify FW, especially at the household level, is the lack of standard methodologies, which has resulted in utilization of numerous methodologies that are substantially different from each other (van Herpen et al., 2019).

2.1.1 Aims of the current study

Considering the absence of a critical and comprehensive review of FW quantification methods, the aim of the current study is to compare household FW quantification methods, with a focus on methods addressing composition analysis. Recent studies related to FW quantification at the household level were reviewed systematically to understand the strengths and limitations of the quantification methods each study has used. This paper presents a critical comparison of the methods and indicates the strengths and limitations of each method, which is useful for future researchers in selecting the best method that caters to their study requirements.

The first section of the paper presents background information and the study context related to food loss and waste and justifies the need of the present study. Section two presents the methodology used for the current literature review. In the results and discussion section, a short analysis of bibliographic information is presented first, followed by the in depth analysis of four different FW quantification methods: surveys and interviews; kitchen diaries; waste audits; and secondary data. Strengths and weaknesses of each of the methods are discussed in detail and an overview of all methodologies and their applicability are discussed. The recommendations and conclusions section presents guidance for future researchers on the applicability of each method for different study contexts.

2.2 Background

2.2.1 Food Loss and Waste

FAO (2014) defines ‘food’ as any substance which is intended for human consumption, either processed, partially processed, or raw. This definition is inclusive of any drinks, chewing gum, and any other substances that have been used during manufacturing, processing and treatment of ‘food’. However, the food that is intended for human consumption frequently gets lost or wasted at each stage of the food supply chain (FSC), from agricultural production to final consumption, in other words, from farm to fork (Xue et al., 2017). In general terms, this ‘food’ becomes ‘waste’ when it loses its quality or when it is not consumed by humans within the utility lifespan (FAO, 2011).

There exist a number of definitions around food loss and food waste. One of the widely accepted definitions are from FAO (2014) where ‘food loss (FL)’ is defined as the “decrease in quality or quantity of food” that occurs at the initial production and distribution segments of the food supply chain (FSC) (FAO, 2014a). FL usually takes place due to inefficiencies in the food supply chain such as inadequate management in storage facilities, technological failures in refrigeration, and poor infrastructure during transportation (FAO, 2014a). An important part of food loss is ‘food waste (FW)’, which refers to the intentional removal of food from the FSC, that is still fit for consumption . FW is more often considered to occur by choice, for example, surplus preparation and neglecting which results in spoiled, expired or surplus uneaten food (CEC, 2017). However, some studies distinguish FL and FW solely based on the stage in which it is generated (van der Werf & Gilliland, 2017). These studies consider the decrease in edible food mass at the production, postharvest, and processing stages as FL, and food lost at the level of retailers and consumers as FW (van der Werf & Gilliland, 2017). This common distinction between FL and FW is illustrated in Figure 1.

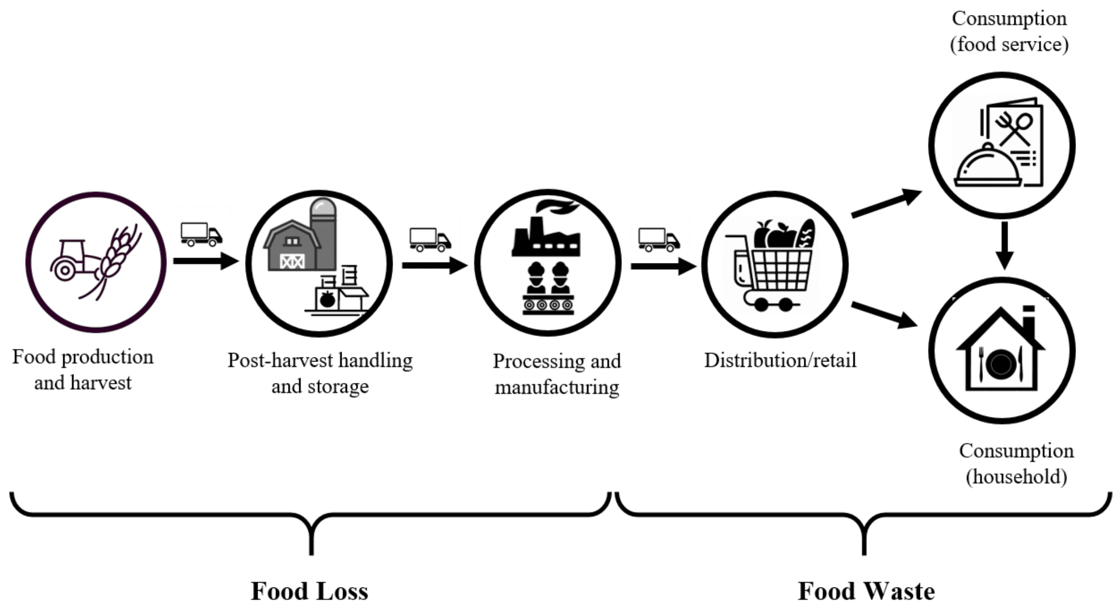

Figure 1: Overview of food supply chain and the distinction between food loss and food waste (based on the information presented by Gooch & Nikkel (2019) and van der Werf & Gilliland (2017))

FW is further classified into a number of categories, edible and inedible avoidable, possibly avoidable and unavoidable (Quested & Johnson, 2009). The latter categorization was first introduced by the Waste Reduction Action Program (WRAP) of the United Kingdom in 2009 (Quested & Johnson, 2009) and has been adapted more frequently in FW studies ever since (e.g. Delley & Brunner, 2017; Edjabou et al., 2016; Parizeau et al., 2015; van der Werf et al., 2018). Avoidable FW is the food that was edible at some point prior to disposal. For example, food that has spoiled or reached its best before date and discarded are considered avoidable (FUSIONS, 2014). Food that some individuals eat but others do not, such as potato peels, beet greens, and bread crusts is considered possibly avoidable. Food that is not edible under normal circumstances, such as orange peels, meat bones, and egg shells is considered unavoidable

(Quested & Johnson, 2009). However, the classification of FW into these categories may depend on cultural factors, and what food belongs to each category may change over time (Kummu et al., 2012). Although categorization based on avoidability or edibility are the most frequently used methods, a range of other classification methods can be found in FW literature. (Garcia-Garcia et al., 2017) presents 9 different FW classification methods based on different indicators such as origin (animal/plant based), complexity (single/mixed product), presence of animal products, treatment (processed/unprocessed), packaging etc.

2.2.2 Impacts of food loss and waste

Food loss and waste that occurs throughout the FSC has recently attracted global attention due to its adverse impacts not only on the environment, but also on the economy and society on a broader scale (Garcha, 2017;). When the economic burden is considered, the associated monetary value of lost food alone across the globe is approximately $750 billion annually (FAO 2011). According to FAO estimates, the total economic cost of food wastage is about $1 trillion each year (FAO, 2014b).

Environmental impacts related to FW (associated with impacts of producing food that is wasted), range across a number of concerns including use of water, land, fertilizer and energy, as well as loss of biodiversity and climate change. According to FAO estimates, the annual global food loss and waste has a carbon footprint of 3.3 Giga tonnes of CO2 equivalence without accounting for GHG emissions from land use change, ranking FW the third highest GHG emitter after USA and China (FAO, 2013) In addition to economic and environmental costs, FW incurs a vast range of social costs. Resource depletion and pollution from agricultural production of lost or wasted food leads to food security risks, loss of livelihoods, individual and societal health costs, and loss of well-being and societal value due to loss of habitat and landscape amenities (FAO, 2014b).

2.2.3 Household FW and the gaps in existing knowledge

Although food is lost or wasted throughout the food supply chain, many studies report that in developed countries, the highest percentage of food loss/waste happens in the post consumption stage, especially at households (Bräutigam et al., 2014; Gooch & Felfel, 2014; Parfitt et al., 2010). Although, a recent study in Canada reported that households are responsible for only 14% of total FLW and 21% of avoidable FW (Gooch & Nikkel, 2019), there is still a significant uncertainty regarding the quantity of FW generated at households. Large quantities of FW from the household sector result in high costs for collection and transport, as well as for separation and treatment in waste management facilities (Bräutigam et al., 2014). Due to this significant contribution, focusing on household FW is important as it plays a major role in meeting FW reduction targets at local as well as global level. For instance, the Goal 12 of United Nations Sustainable Development Goals (SDGs); "Ensure sustainable consumption and production patterns" includes amongst its targets to "halve per capita global FW at the retail and consumer level, and reduce food losses along production and supply chains by 2030" (United Nations, 2015). Thus, it is evident that additional attention is needed to understand and reduce household FW due to its substantial contribution to FW generation.

One of the key approaches towards handling FW issues would be measuring, tracking and reporting the quantities and composition of waste generated across the food supply chain, as it is not possible to manage something that is not measured (Rajan et al., 2018). However, several researchers have identified lack of knowledge and methodological gaps in quantifying FW generation as the major obstacles in addressing FW generation (Chaboud, 2017; Edjabou et al., 2016; Eriksson et al., 2012; Parizeau et al., 2015). When household FW generation is considered, it is essential to clearly understand the quantity and the composition of FW generated in order to change the household waste behavior (Parizeau et al., 2015). Without this knowledge, it is difficult to target, prioritize, and design actions to prevent and reduce food loss and waste.

The lack of a standard and widely accepted methodology for quantifying amounts and composition of household FW has led researchers to adopt numerous methods, including waste audits, kitchen diaries, surveys, and estimations based on secondary data (Bräutigam et al., 2014). Many recent publications have recognized the inconsistencies in these numerous methodologies for quantifying FW as a limitation which restricts valid comparisons among different studies (Edjabou et al., 2016; Elimelech et al., 2018; Parizeau et al., 2015; van Herpen et al., 2019; Xue et al., 2017).

The previous review articles by Xue et al. (2017) and van der Werf & Gilliland (2017) present an overview of FW research that was published before 2014 and 2015, respectively. Moreover, both these studies focused on the entire food supply chain, thus overlooking the specific methodological barriers for quantifying household FW. Although Schanes et al. (2018) reviewed studies on household FW until the year 2017, their focus was specifically on FW practices as well as distilling factors that foster and impede the generation of FW at the household level. Given that none of the publications have attempted to compare the strengths and weaknesses of each methodology in a comprehensive manner, we provide a detailed review of household FW quantification methods to identify gaps for future research.

2.3 Methodology

In this study, a systematic literature search approach was used, employing a scholarly data base and pre-defined key words, as shown in Figure 2. Through initial screening of related literature, a set of keywords to represent FW scenarios, specifically at the household level, was selected. The selected key words were "food waste" or "residual waste" or "household waste" or "food loss" or "food loss and waste" or "green bin" or "organic waste" and "households" or "homes" or "consumer" or "residential". The above keywords were used to search Scopus database for publications and peer reviewed journal articles related to household FW published within the time frame of January 1, 2010 to April 15, 2019.

The initial screening for selecting the relevant studies was done by reading the titles of the studies. At this stage, in order to prevent relevant studies from being excluded, all the studies that addressed any component related to FW/organic waste/residual waste were selected. This resulted in 366 studies, which were then subjected to the second step of screening.

The second screening was done by reading the abstracts and reviewing the full articles where necessary to select studies that specifically addressed quantification and/or composition analysis of household FW. The following inclusion/exclusion criteria were used for the second screening: (a) published within January 1, 2010 and April 15, 2019; (b) published in English language; and (c) quantified and/or analyzed composition of FW generated at households. Out of the 366 studies that were subjected to the second screening, 45 studies were selected for the in-depth review of methodologies. While screening out the studies relevant to the above mentioned criteria, all 366 articles were broadly categorized into 9 categories to obtain a broad overview of the related literature.

Strengths and weaknesses of each FW quantification method were identified by conducting a simplified conceptual content analysis of the selected journal articles, using general guidelines provided by Thomas and Harden (J. Thomas & Harden, 2008) and White and Marsh (White & Marsh, 2006). The research question was "What are the strengths and weaknesses associated with various FW quantification methods?" Using an inductive approach, each paper was read thoroughly to identify phrases that represented various concepts related to strengths and weaknesses of quantification methods, such as: 'accuracy', 'cost/expensive/inexpensive', 'subjective/objective/bias', 'composition analysis/ability to analyze composition', 'response rate', 'sample size', 'ability to track alternative means of disposal', 'ability to track root causes' and 'technical expertise.' Regardless of the number of phrases mentioned in the study related to each concept, the researcher only counted the presence of each concept as one occurrence, but noted the context of the phrase to obtain a more nuanced analysis. For example, if an article mentioned a method as being 'expensive', the conditions that made it were noted, such as 'expensive if subjects are compensated.' Results for each paper were summarized and then synthesized across all the papers into broader categories of strengths and weaknesses (e.g. Strengths: Large sample size is possible; Weakness: Needs a significant effort from the participants such that tapering enthusiasm of respondents can be problematic).

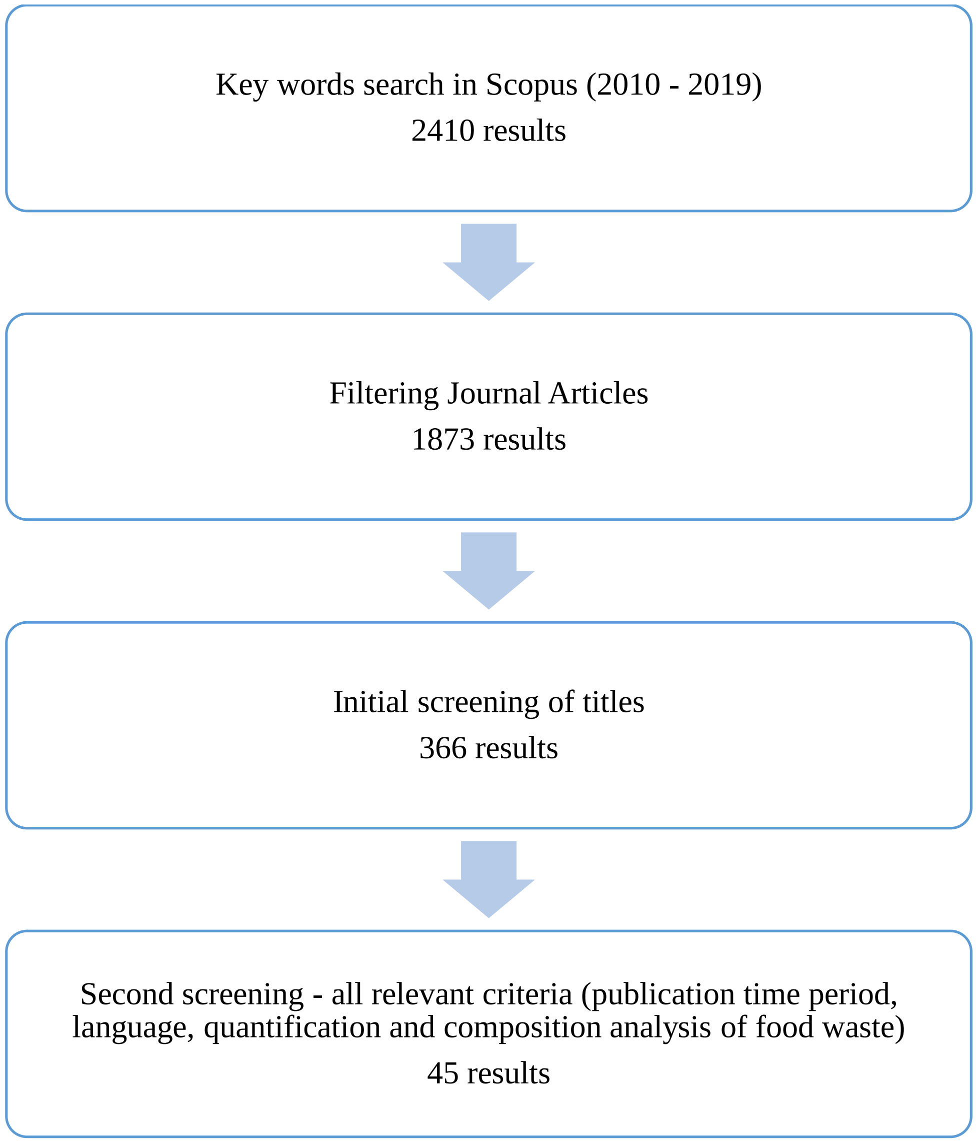

Figure 2: Summary of the literature review methodology

2.4 Results

The results are presented in two major categories: 1) meta-analysis of studies reviewed; and 2) critical review of available methods for quantifying household FW.

2.4.1 Studies reviewed

2.4.1.1 Analysis of bibliographic information

The bibliographic information of the 366 studies that passed the initial screening of titles shows how the number of publications related to FW has increased steadily over the last decade, with a three-fold increase from 2013 to 2018 (Figure 3). This justifies the need of the current review, which captures the more recent studies that were not included in the previous reviews by van der Werf & Gilliland (2017) or Xue et al. (2017).

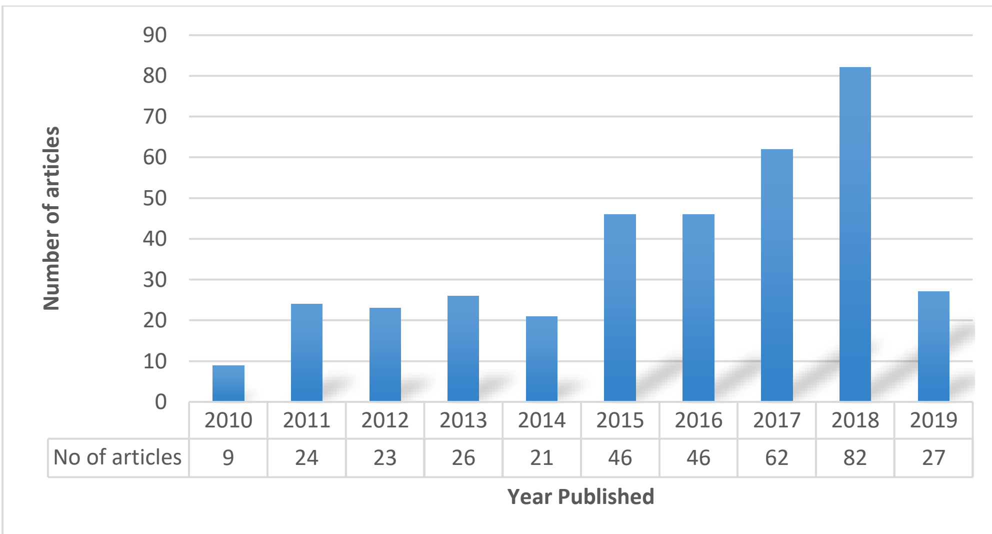

Figure 3: Number of articles related to food waste published from 2010 to May 2019 within the search criteria of the current study (*This does not represent all publications related to food waste but only the ones that appeared within the search criteria of the current study*).

The selected 366 studies from the first screening are grouped according to country or territory to understand the geographical distribution of the recent FW studies. This classification was done based on the country that the study was carried out or the country of the first author (in studies that did not have a clear geographical boundary). According to this analysis, most of the FW research is concentrated in industrialized countries, especially in Europe, where more than 250 out of 366 studies were carried out (Figure 4). The highest number of studies is recorded in the United Kingdom (64 studies) followed by 53 in the USA, 35 in Italy, 31 in Sweden and 26 in Denmark. This attention to FW in Europe may be due to the numerous action plans, regulations and legislations on FW put forward by the European Union (Vittuari et al., 2015) during the past decade. In contrast, only a handful of studies have been carried out in developing countries, especially in South Asian or African region. This may be because in developing countries food is seldom wasted after purchasing as poverty and limited income make it unaffordable to waste food, as some researchers argue (Ericksen, 2008; FAO, IFAD & WFP, 2015).

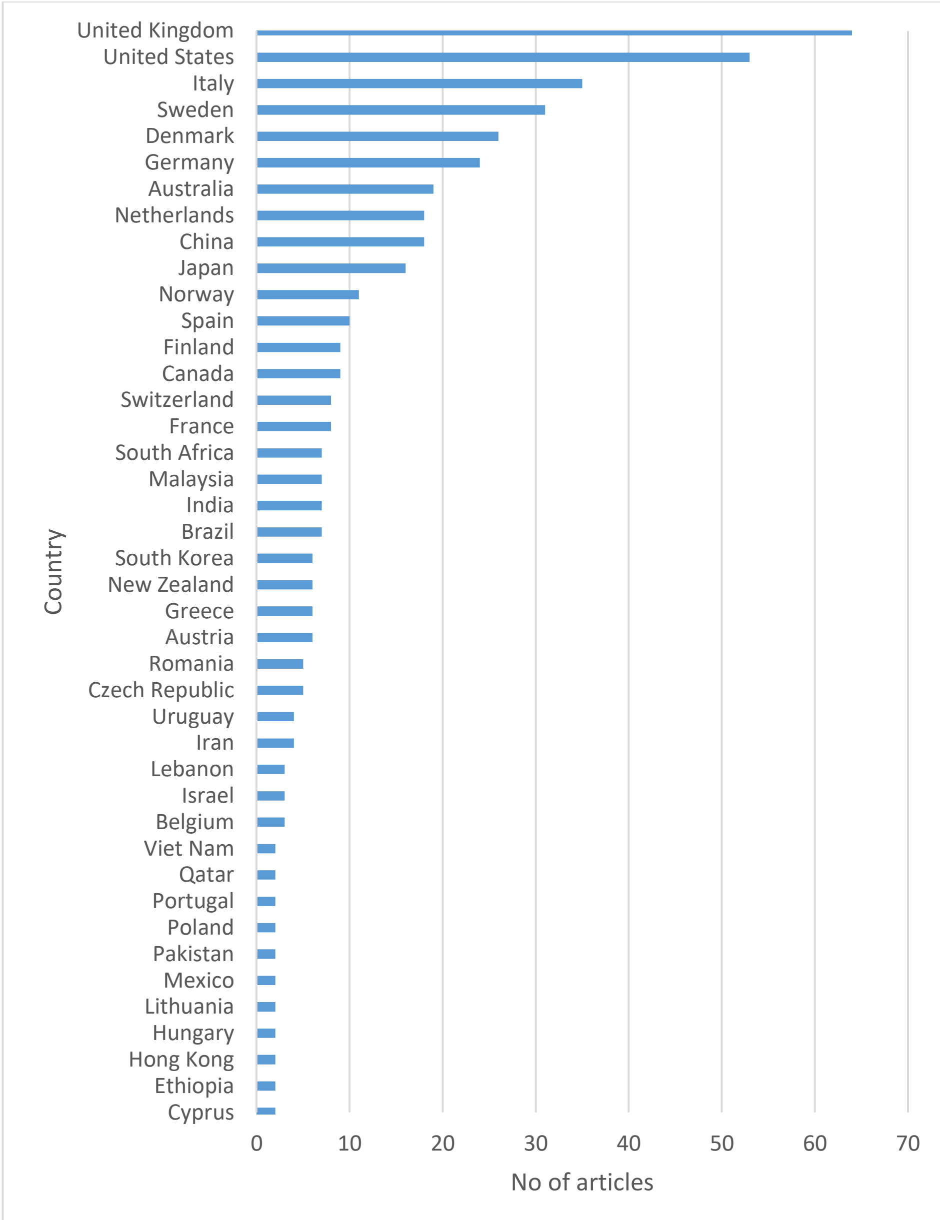

Figure 4: Number of articles by country from 2010 to 2019.

The top five academic journals ranked in order of number of publications were Waste Management (47 articles), Journal of Cleaner Production (38 articles), Resources Conservation and Recycling (27 articles), British Food Journal (17 articles), and Waste Management and Research (12 articles).

2.4.1.2 Categorization of articles

As explained in the methodology section, all the articles that passed the first screening were then categorized into nine broad categories according to their study objectives. Although the main intention of this second screening was to select the most relevant articles that quantified FW generated at households (which is shown as Category 3 in Table 1), this categorization provided a broad overview of the selected literature (Table 1).

The second step of the screening process led to the categorization presented in Table 1. This categorization was primarily based upon the main objective or the primary research question each study was attempting to address. All studies in which the main objective was to assess the food wasting behaviors, and not to quantify FW were included in Category 1. During this second screening, it was observed that the majority of household FW studies have focused on assessing behavioral aspects of FW generation, rather than attempting to quantify the actual amounts. Most of these studies used surveys or interviews to study attitudes and behaviors shaping food wasting behaviors at households. Some of the studies specifically looked at parameters such as packaging, shopping behavior, price and suboptimal food in relation to wasting behaviors. Since these studies did not specifically look at quantities or composition of FW at households, all studies in this category were excluded from further review.

Table 1: Categorization of articles according to their study objectives

Category	Description	# of articles
1	Studies on food wasting behaviors, drivers and barriers	116
2	Studies that quantified residual household waste including organics (where study objective is not food waste specifically)	54
3	Studies that quantified the amount and/or analyzed composition of household food waste	45
4	Studies with a broader scope that covered more than one stage of food supply chain	32
5	Studies that focus on other stages of consumer food waste (retail/food services)	17
6	Studies that discussed Climate Change aspects of food waste	14
7	Policy reviews and policy implications related to food waste	13
8	Literature reviews and Meta-Analysis	6
9	Other (studies that could not be categorized into any of the above categories)	67
	TOTAL (*Two articles were not accessible)	**364**

Category 2 includes the studies that quantified residual household waste, including organic wastes. All studies in this category were focusing on all streams of residual household waste including organics, recyclables and garbage. Although some of these studies used similar methods discussed in this review such as surveys and waste audits, those methods were used in a rather generic manner and not specific for FW. For instance, in residual household waste audits, composition analysis would focus on categorizing the waste into categories such as paper, plastic, metal and organics; or recyclables, organics and garbage. These studies did not further analyze the organic fraction and thus, overlooked the specific parameters that are important in a FW composition analysis. As these studies lacked the specificity for quantifying FW, this category was also excluded from further review. However, there were 45 studies that specifically aimed at quantifying the amount and/or analyzing the composition of FW generated at households. Since the current review aims at identifying and analyzing the methods of FW quantification and composition analysis, studies in this category were further reviewed for their methods.

The key word search brought up a large number of studies that could not be included in any of the above three categories. Depending on their main focus, they were categorized into seven more categories (Category 4 to 9) as shown in Table 1.

2.4.2 FW quantification and composition analysis methods

All 45 articles in Category 3 were thoroughly reviewed to identify their methodologies and to draw comparisons. FW quantification methodologies (Figure 5) identified in the analysis were: (i) surveys and questionnaires; (ii) kitchen diaries (self-reported); (iii) estimations based on secondary/aggregate data; and (iv) waste audits (direct measurement of wet weight). There were a number of studies that incorporated more than one of the above methods (Rispo et al., 2015; Khalid et at., 2019; Sosna et al., 2019; Xu et al., 2016), while there were also studies that compared two or more methods (Delley & Brunner, 2018; Giordano et al., 2018; van Herpen et al., 2019).

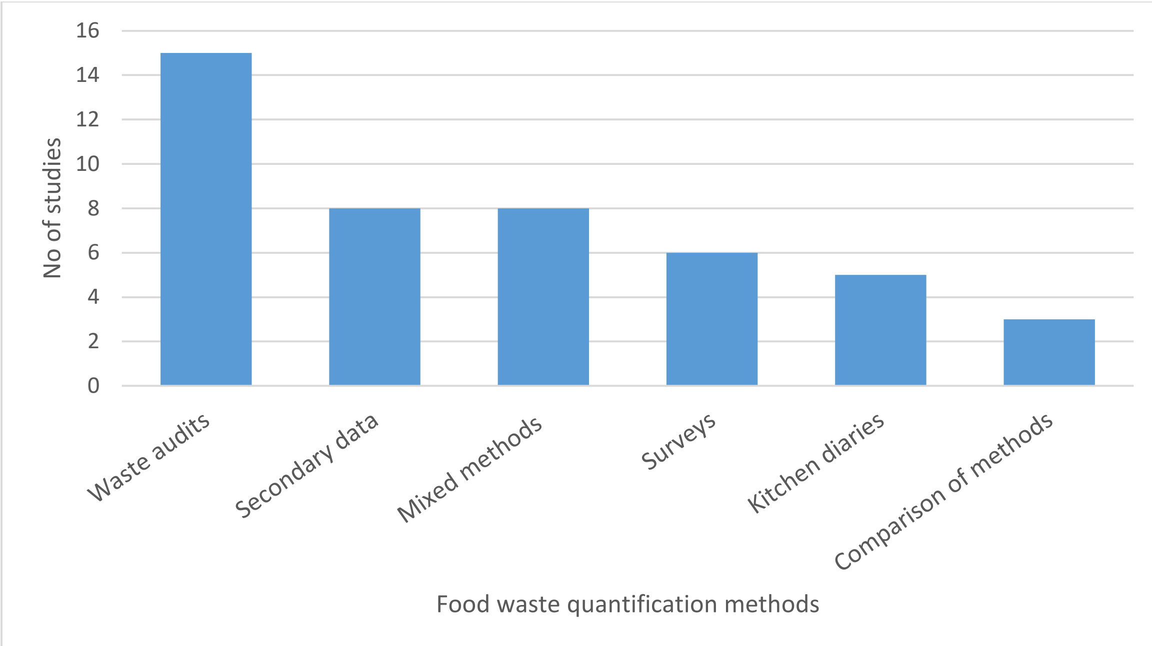

Figure 5: Number of articles based on the quantification method used for Category 3

2.4.2.1 Surveys

In this review, surveys are defined as a method which utilizes a questionnaire as a tool to capture self-reported quantities and the composition of FW generated within a respondent's household, and sometimes includes questions on demographics and behavior related to FW. Surveys can be self-administered (respondents answer the questions either online or with a paper and pencil survey) and primarily rely on a third party other than the researchers (van Herpen et al., 2019). They can also be researcher-administered (researcher asks questions and records answers from the respondent via telephone or in-person). In surveys, responses are recorded based on a single instance. Measures of FW typically include absolute or frequency measures (how often), visually-based measures (visual aid provided to judge quantity), to proportional waste measures (as a percentage or fraction of food consumed) (CEC, 2019). Of the 45 articles reviewed, six articles primarily used surveys as the data collection method

(Table 2). Six other studies that coupled surveys with another method/methods will be discussed in section 4.2.5.

Table 2: Studies that used surveys to quantify household food waste

Article	**Country**	**Sample Size**	**Method**
Aschemann-Witzel et al. (2019)[1]	Uruguay	540 households	Survey (online) with open-ended questions asking respondents to describe their most recent food wasting incident in terms of what was wasted, why and when.
Jörissen et al. (2015)[2]	Italy & Germany	857 respondents	Survey (online) of employees of two scientific institutions. Covered only avoidable FW, studied household behavior (shopping, food preparation and eating) related to FW over a week.
Lanfranchi et al. (2016)[3]	Italy	500 respondents	Survey (online) estimated the food waste at five levels; "much, relatively, a little, very little, nothing"
Martindale, (2014)[4]	UK	100 respondents	Survey (online) estimated the proportion of frozen and fresh food wasted daily using graphical illustrations. These estimates were used to calculate a waste index.
Visschers et al. (2016)[5]	Switzerland	796 households	Survey (paper and pencil mailed to households). Self-reported FW indicated the frequency of wasting and the amount across 11 different food categories over a week.
Zhang et al. (2018)[6]	China	418 households	Explored the nature of the FW produced, including its quantity as a percentage of the food consumed, the proportion of avoidable and non-avoidable waste and the composition of the FW generated

Only one study was researcher-administered at the visiting households (Zhang et al., 2018). Out of the self-administered surveys, one study (Visschers et al., 2016) sent out a pencil and pen survey by mail, while the remaining four studies used online surveys. All surveys included a section where respondents' demographic information was recorded. Aschemann-Witzel et al. (2019) asked respondents to recall only their most recent FW instance, while all other studies asked respondents to recall FW generation over a week. Most of the studies also considered the type of food being wasted and the reason for food wastage. Nevertheless, there is inconsistency on what is being recorded, particularly with respect to amount of waste, which was recorded as relative to absolute values.

Strengths and weaknesses of surveys

The strengths and weaknesses of surveys in quantifying FW as discussed in the reviewed studies are summarized in Table 3.

Surveys are considered a cost-effective method to generate rough quantitative estimates of FLW at every stage of the food supply chain (CEC, 2019). Although some researchers argue that the response rate for surveys could be rather low unless a monetary incentive is provided for respondents (van Herpen et al., 2019), the ever-increasing access to internet, administering online surveys allow researchers to reach more people, thus resulting in a large sample size (e.g., 796 households in Visschers et al. (2016), and 857 households in Jörissen et al. (2015)).

Table 3: Strengths and weaknesses of surveys.

Strengths	Weaknesses
• Possible to assess FW composition [1,2,3,4,5,6] • Can obtain data on demographic and other characteristics of respondents [1,2,4,5,6] • Wide reach and allows larger sample size [1,2,3,5,6] • Can assess causes of FW [1,2,3,5,6] • Relatively low cost [1,5]Can assess the effectiveness of interventions related to behavioral aspects [2] • Researcher-administered surveys allow clarification of questions [5]	• Self-reported FW quantities can be less accurate, with a tendency to underestimate [1,2,4,5,6] • Response rate can be low [2,3,4,5] • Respondents may be inclined to give socially-desirable responses [1,2,5,6] • Researcher-administered surveys can be costly and time consuming [1]

Importantly, surveys can be quite beneficial when the researcher does not have direct access to FW disposed by households (Martindale, 2014). Surveys may also capture FW disposed using alternative means such as composting, pet food, and over the sink (Aschemann-Witzel et al., 2019). In addition, surveys often collect demographic information of the participants, making it possible to examine correlations between amount of waste generation and other factors such as income, age, number of family members etc.

A notable strength in surveys is their ability to examine FW composition, as well as root causes, drivers, and barriers of food wasting behaviors. For example, Aschemann-Witzel et al. (2019) studied the categories of food being wasted (e.g. rice, vegetable, baked goods, etc.), the reason for wasting (e.g. bad quality, prolonged storage, reached expiration date, etc.), and the situation in which waste occurred (e.g. food preparation, eating, cleaning fridge, etc.). Visschers et al.

(2016) recorded the frequency of FW occurrence in 11 different food groups, while also assessing intentions to avoid FW, attitudes and behavioral norms.

Despite these strengths, surveys have a range of limitations. One of the major limitations in using surveys for FW quantification is that surveys solely depend on recall and self-reported estimates and measurements, which leads to several problems.

Firstly, the measures are inconsistent across different studies making it challenging to draw comparisons among them. For instance, some studies require the respondents to record their FW in absolute measures of weight such as in grams per meal or per day or per week (Jörissen et al., 2015). This could be difficult for participants considering that wasting food is an unintentional behavior. It would be difficult to recall exact FW quantities over a given time period (Aschemann-Witzel et al., 2019).

Secondly, self-estimation without actual weighing can be inaccurate. There are some approaches used to mitigate this. Martindale (2014) used illustrations to help respondents decide the amount of FW (shapes proportional in size to the amount of FW), while Visschers et al. (2016) used portion size (e.g. x number of portions; portion size being one handful of food served) as a measure of FW as well as frequency of occurrence (e.g. number of times per week/month, to less often or never) in each type of FW category. Zhang et al. (2018) asked respondents to recall the amount of FW as a percentage of total household waste as well as the amount of avoidable FW as a percentage of total FW. Aschemann-Witzel et al. (2019) asked the respondents to record their most recent food wasting incident instead of recording the daily or weekly FW amounts, arguing that it is more accurate than arbitrary estimations in overall terms. However, this may not be representative of the FW quantities over a period of time considering that the study takes into account only a single instance for each participant. A study by Lanfranchi et al. (2016) asked the respondents to express their FW amounts in terms of categories ranging from ‘much’, ‘relatively’, ‘a little’, ‘very little’, to ‘nothing’. However, this is highly subjective because an individual’s perception of quantity in terms of ‘much’ or ‘a little’ could differ from that of another individual which would result in unreliable estimates. Regardless of the applicability and representativeness of each of these methods, the inconsistency of measurement leaves little to no room for comparison across different studies. Comparison of FW quantities and composition among different studies is important to understand how FW generation changes between different geographic regions depending on their socio-cultural, economic or political background, or in the same geographic region over time to develop appropriate reduction strategies.

Thirdly, respondents might intentionally under-report actual amounts of FW, or unintentionally over/under-estimate the amount as wasting food is considered a negative and non-appealing behavior in society; this would lead to incorrect estimations of actual FW generation (Aschemann-Witzel et al., 2019). Further, Hebrok & Boks (2017) argue that since self-reporting depends on respondents’ ability to understand, recall and record, this can affect the validity and accuracy of the results. Although pre-announcing a survey may reduce this effect, it does not necessarily eliminate it since respondents may be inclined to give socially-desirable answers regardless (van Herpen et al., 2019). Thus, it is evident that the accuracy of the estimates obtained from surveys could be highly uncertain.

2.4.2.2 Kitchen Diaries

In this review, kitchen diaries refer to the practice where the respondents (typically residents of households) keep records of the amount and nature of FW generated at their homes on a regular basis. This method often requires the respondents to measure and record the amount (i.e., weight or volume) and the type of food being wasted, along with the reasons and situations under which FW occurred (CEC, 2019). Unlike surveys, kitchen diaries record amount of FW as it occurs, and usually over a longer period of time.

Of the studies reviewed, five studies used kitchen diaries to quantify FW at households (Table 4). Sample size varied from 20 households to 385 households and the majority of the studies recorded FW over a period of one week. However, one study had a duration of two weeks (Silvennoinen et al., 2014), while another recorded weekly FW amount for over a period of eight months (AlMaliky & AlKhayat, 2012).

Two of the studies (Giordano et al., 2019; Richter & Bokelmann, 2017) focused on shopping habits and purchases to understand relationships between what was purchased and what was wasted. Only two studies evaluated FW composition (Giordano et al., 2019; Williams et al., 2012).

Table 4: Studies that used Kitchen Diaries to quantify FW at households

Article	Country	Sample Size	Approach
Al-Maliky & ElKhayat (2012)[7]	Iraq	20 households	Weighed and recorded weekly food purchases and waste for eight months using kitchen scales.
Giordano et al. (2019)[8]	Italy	385 households	Shopping habits and FW quantities were recorded in a daily diary to explore the relationship between purchasing discounted food and FW. Edible and inedible FW quantities recorded with the type of food.
Richter & Bokelmann (2017)[9]	Germany	25 households	Households kept a diary over a period of one week to document food purchases, storage, and amounts wasted. No composition analysis.
Silvennoinen et al. (2014)[10]	Finland	380 households	Participants weighed and recorded all FW upon disposal, along with the reason for disposing; this was done over a period of two weeks.
Williams et al. (2012)[11]	Sweden	61 households	Households measured (weight or volume) and recorded their FW over a period of one week with reasons for disposing. FW was categorized into seven categories of food.

Strengths and Limitations of Kitchen Diaries

A summary of the strengths and limitations of kitchen diaries is provided in Table 5.

A prominent strength of kitchen diaries over surveys is that self-reported amounts are likely to be more accurate and less uncertain with kitchen diaries, because they do not rely on recall, instead asking respondents to record FW quantities at the time of disposal (Richter & Bokelmann, 2017). This eliminates the possibility of unintentional incorrect estimations, although social desirability and awareness of the study objectives can still lead to behavioral change or intentional under-reporting (Langley et al., 2010; van Herpen et al., 2019).

Another strength is that kitchen diaries often require respondents to record the background information associated with wasting of food, such as the reason for throwing away, the condition of food at the point of disposal (whether food is spoiled or reached best before date) as well as the means of disposal (garbage/composting/over the sink) which captures all streams of waste regardless of whether they end up in garbage bin or not (Silvennoinen et al., 2014).

Finally, kitchen diaries allow respondents to record the composition of FW in a more detailed manner than with surveys, as per research requirements. This method is capable of capturing not only the amount of food wasted, but also the type of food and whether it is avoidable or unavoidable (van Herpen & van der Lans, 2019). This is a major strength in FW research as it allows the researcher to capture as much information as possible during the food wasting incident itself. Many researchers argue that diaries are a substitute for detailed observations in terms of observing everyday situations, but without the effect of researcher being present. Thus, diaries can provide detailed information about the daily habits where researchers would normally have no access, and which otherwise would have been neglected (Richter & Bokelmann, 2017). Diaries are also suitable to examine subjective experiences, cognitions, and behavioral aspects of the participants, especially to show how and why people act the way they do. Although surveys are also capable of recalling information, the strength of kitchen diaries over surveys is that diaries record data repeatedly over a definite period of time, during the time of action. In that sense, kitchen diaries would be an ideal method to study root causes of FW, what makes people waste food and what they feel about it as opposed to studying how much waste is actually generated.

Table 5: Strengths and weaknesses of kitchen diaries method

Strengths	Weaknesses
• Provides information about the type of food as well as the root causes [8,9,10,11] • Can provide descriptive information that could not be captured by other methods [8,9,10,11] • Captures FW that does not go into a waste bin [9,10,11] • High accuracy, especially compared to surveys [7,11]	• Possibility of intentional under-reporting [8,9,10,11] • Needs a significant effort from the participants such that tapering enthusiasm of respondents can be problematic [7,9,11] • Can be costly, especially if the participants are compensated [11] • Method itself can lead to changes in behavior [8]

One of the most significant limitations of using kitchen diaries for FW quantification at households is that it requires a great deal of time and effort from both participant and the researcher (Richter & Bokelmann, 2017). On the one hand, if the participants are required to weigh all their FW upon disposal (eg: AlMaliky & AlKhayat (2012)), it results in a high reporting burden on the respondent that could result in low participation rates as well as tapering of enthusiasm of participants with time. This would often result in small sample size compared to the population of interest. For instance, in the study by Silvennoinen et al. (2014), out of 3000 invitations to participate in the study, only 700 people volunteered resulting in a response rate of 23.3%. Out of the 420 households selected according to the study criteria, 40 households did not finish the study acceptably. On the other hand, if the participants are allowed to measure and record their FW according to their own convenience, such as using a variety of measurements (weight/volume/proportion), it would result in a significant burden on the researcher having to transform all measurements into a single standardized unit (Richter & Bokelmann, 2017).

Another frequently cited weakness related to using the kitchen diary method is that it could lead to behavioral changes in participants, which will limit the ability to capture 'business-as-usual' scenario. Since respondents would be more conscious about their wasting habits during the period of participation, recording FW using kitchen diaries could act as a constant reminder and positive motivator for behavioral change (Langley et al., 2010), which could result in declining validity of results over the time period.

2.2.2.3 Direct measurement through waste audits

The current review defines a waste audit as a method where the researcher will directly collect, physically separate waste streams, and weigh and categorize each fraction of waste to generate accurate figures (van Herpen et al., 2019). The current review study identified 14 studies that collected data primarily based on waste audits, among which two studies also had a self-reporting component. The selected studies, their sample size and the FW quantities reported are shown in Table 6.

In waste audits, FW from households is collected, physically separated, weighed and categorized. Often, waste audits primarily focus on the waste that is put out for collection by the households, but the approach for collecting and analyzing samples could be quite different from one study to another. This study identified three specific approaches for sample collection: obtaining samples at the curb when households have put out their waste for collection (Parizeau et al., 2015); providing kitchen caddies for households to dispose their FW instead of disposing into the regular garbage bin (Zan et al., 2018); and obtaining samples from the municipal collection centers (Oelofse et al., 2018).

Table 6: Studies that quantified household FW using waste audits

Source	Country	Sample Size	FW/capita/ week	FW/household/ week	Approach
Lebersorger & Schneider (2011)[12]	Austria	130	0.640 kg		Samples were picked up during the regular waste collection day for weighing and sorting. Sorted according to avoidability, life cycle stage and packaging.
Parizeau et al. (2015)[13]	Canada	222	4.2 kg		Source separated organics weighed on two subsequent garbage collection days collected at curbside and analyzed for composition
Van Der Werf et al. (2018)[14]	Canada	900		2.4 kg	FW composition audit data from 9 municipalities-curbside weekly collection – data from 2012 – 2015
Simunek et al. (2015)[15]	Czech Republic	17		1.01 kg	Daily logs for food waste and food purchase, for a period of three weekdays and one weekend, this later estimated to a weekly amount, food was discarded into separate plastic bags provided, and afterwards audited to compare with the logs
Sosna et al. (2019)[16]	Czech Republic	9	0.312 kg - 0.637 kg		Waste collected by municipality, sampled separately for each household, cost is also recorded
Stejskal et al. (2017)[17]	Czech Republic	18		53-58.5 kg per year	FW categorized into eight fractions, separately weighed and analyzed weekly
Edjabou et al. (2016)[18]	Denmark	1474		3.51 kg	One week of waste from apartments, bi-weekly collection from single family households, sorted into six food waste fractions, which were then sorted further into detailed fractions and then grouped into an additional 11 food categories
Edjabou et al. (2018)[19]	Denmark	101		9.6 ± 4.5 kg – autumn 9.9 ±5.1 kg – summer 9.2 ± 5.2 kg - winter	Samples collected by municipal waste collection for a full week in each of the three seasons, spring, summer, and winter. No composition analysis
Elimelech et al. (2018)[20]	Israel	192	1.82 kg		Daily collection at doorstep, same day sorting, for seven consecutive days, composition analysis included

Source	Country	Sample Size	FW/capita/ week	FW/household/ week	Approach
Gutiérrez-Barba (2013)[21]	Mexico	41	2.24 kg		Waste samples collected pre and post awareness program – weekly collection
Hanssen et al. (2016)[22]	Norway	220		3.76 kg	Four municipalities with no source segregation, collected weekly by municipality collection from each household separately weighed and analyzed, each food category weighed separately
Khalid et al. (2019)[23]	Pakistan	51	0.426 kg		Plastic bags were given to the households to keep their one day (24 h) food waste. Separate bags for each FW fraction which was weighed separately
Chakona & Shackleton (2017)[24]	South Africa	200	0.42 kg		Self-reported waste audit - FW recorded and measured at disposal (in cups, Tea spoons, Table Spoons etc.)
Oelofse et al. (2018)[25]	South Africa	65366		0.585 kg	Bulk sampling with randomized grab sampling, bulk sampling - weighing the municipal collection each week (weighing trucks), random sample of 100-200 g taken from each truck load and analyzed for composition.
Bernstad et al. (2013)[26]	Sweden	680		2.0 - 2.5 kg	Source separated organics from all households and 50% of residual waste bins analyzed for composition (several categories of avoidable and unavoidable FW)

Strengths and Limitations of Waste Audits

The summary of the strengths and limitations of waste audits is presented in Table 7. Compared to other waste quantification and characterization approaches, the biggest strength of waste audits is that it has high validity and data quality, as it does not rely on self-reported amounts (van Herpen et al., 2019). Since the researcher is recording FW quantities instead of the participants, it eliminates the probability of intentional under-reporting (Parizeau et al., 2015).

Table 7: Strengths and weaknesses of waste audits

Strengths	Weaknesses
• Can provide detailed information about the composition [12, 13,14,15,16,17, 18,19,20, 22, 23, 24, 25,26] • Avoid the bias due to social desirability unless respondents are given special bins [12, 13, 14, 15, 16, 18, 19, 20, 21, 25] • Allows to track progress over time [12, 14, 17, 19, 21, 25, 26] • Can capture the "business-as-usual" scenario without changing respondents' behavior [15, 13, 19, 22, 25]	• Cannot capture FW disposed in alternative means other than waste bin [12, 13, 14, 18, 20, 25, 26] • Need direct access to FW [13, 14, 16, 19, 20, 23, 26] • State of degradation of FW material can challenge the accuracy of measures [12, 13, 18, 19, 20, 24, 25] • Can be relatively expensive and time consuming [12, 13, 14, 20, 25, 26] • Might not be able to track root causes [12, 14, 16, 22, 25, 26] • Need technical expertise [14, 18, 20, 25, 26] • Ethical sensitivity [13, 14, 20]

Another strength is waste audits are capable of analyzing FW composition, even though a detailed study would be time consuming and arduous. Moreover, waste audits generate high quality data that could be used for comparison with other geographical regions or over time although it demands a considerable scientific knowledge and physical resources such as transportation and sorting facilities.

However, this method requires significant expertise, time and cost (Parizeau et al., 2015; van Herpen et al., 2019). Although the basic approach to waste audits is physically collecting and measuring FW, each waste audit can significantly differ according to the sample (each household vs. whole municipality), sample size (no of households), sampling duration (daily vs weekly), and method of collection (curbside/ municipal collection point/ kitchen caddies).

The most frequently used approach for waste audits is collecting samples at the curb, when the households have set out their garbage bins for collection by the municipal truck. If the households were not informed about the study objectives prior to sampling, this method imposes no bias or behavior alterations in the participating households (Lebersorger & Schneider, 2011). Most of the studies that employed this method have collected samples on a weekly basis to be representative of the food habits of the household (Parizeau et al., 2015), while some studies repeated the weekly measurements for a longer time period to avoid any bias (Stejskal et al., 2017). However, the main drawback of the weekly sample collection is that it could be difficult to identify or categorize certain food items due to decomposition over time. Moreover, this method does not capture the food that was discarded apart from the garbage bin (sink drain/home composting/animal feed) (Parizeau et al., 2015). Additionally, depending on the time of year, FW amounts and composition could change (Edjabou et al., 2018).

Providing kitchen caddies for disposing of FW at households is considered as a more inclusive approach as participants can be instructed to dispose all their FW in the caddies to avoid disposal by other means (Elimelech et al., 2018). Yet, mistakenly throwing food into the regular bin out of habit or the concerns over social desirability associated with FW might lead to underreporting of quantities in this approach too (van Herpen & van der Lans, 2019). This in turn introduces bias into the study as participants are conscious about their food wasting habits resulting in unintentional behavioral changes (Urrutia et al., 2019). Another limiting factor can be the participation effort involved, which although is relatively low for the household participants, effort for researchers can be quite high due to the requirement of visits to individual homes (Elimelech et al., 2018). Moreover, ethical concerns are a frequently overlooked limitation in waste audits, since researchers have direct access to waste generated by the participating households during the audit and can witness alcohol consumption, drugs or erotic material.

Both of the above approaches usually consider each household as a single data point, and thus are able to correlate waste generation with household characteristics if needed. Moreover, these approaches can also observe the changes in food wasting behavior over a period of time, for instance before and after interventions. The third approach where the samples are obtained at the municipal collection point instead of individual houses is a less exhaustive method, however, it is not able to capture information associated with individual households (Oelofse et al., 2018). A positive point of this approach is that it does not require the researcher to visit households and the households are also unaware of the study, which eliminates any bias due to household behavior.

2.2.2.4 Estimates based on secondary data

Another method that was found in the FW literature is using secondary data from previous FW studies at the household level, along with consumption or national or regional FLW estimates, to generate FW estimates at the household level. This method is significantly different from all other household FW quantification methods since there are no observations or recording of FW quantities at the household level. This is an indirect FW quantification method that uses modelling, use of proxy data or use of literature data to estimate FW quantities (Caldeira et al., 2017). The present review found eight studies that used such secondary data, often coupled with a modelling based approach, to estimate quantities of FW generated at households (Table 8).

In general, many such studies (Buzby & Hyman, 2012; Vanham et al., 2015) refer to global level estimates by FAO or United States Department of Agriculture (USDA) database (Xue et al., 2017) and then combine with previously published studies from the same region or similar regions, as well as modeling to address questions such as: the magnitude of the problem (raising awareness) and the economic costs to society of household FW, both direct (consumer) and indirect (municipal waste collection and landfills) (e.g. Nahman et al., 2012);

understanding regional differences in avoidable and unavoidable FW to target interventions; and do scenario modeling for future reductions of avoidable FW (e.g. De Laurentiis et al., 2018)

Table 8: Studies that estimated household FW using secondary data

Article	Country	Approach
Buzby & Hyman (2012)[27]	United States of America (USA)	USDA data was used to generate aggregated values for total food loss in US
De Laurentiis (2018)[28]	European Union (EU)	Household level avoidable & unavoidable waste of fresh fruits and vegetables are estimated for the EU28; unavoidable - considering the inedible fraction of the purchased amount, avoidable -based on results from previous studies
Lusk & Ellison (2017)[29]	N/A	Modelling based approach using household production model by Becker (1965)
Nahman et al. (2012)[30]	South Africa	Aggregate data from previous studies used to generate average values for South Africa
Reynolds et al. (2014)[31]	Australia	Data from three complimentary Australian studies incorporated with WRAP data. Modelling based approach using a weighted average method in conjunction with a Monte-Carlo simulation
Secondi et al. (2015)[32]	EU	Data from 2013 Flash Eurobarometer survey (n. 388) was coupled with study carried out by the BIO Intelligence Service (Monier et al., 2011), and used a modelling based approach to estimate FW for EU-27 countries

Article	Country	Approach
Song et al. (2018)[33]	China	Data from China Health Nutrition Survey was modelled using Bayesian Belief Network system to identify reduction scenarios
Vanham et al. (2015)[34]	EU	Data from FAO Food Balance Sheets were used in a statistical model

Strengths and Limitations of Secondary Data

A main strength of this approach is that it is cost effective and less time consuming than more direct methods (Table 9). Secondi et al. (2015) and Song et al. (2018) used data from previous nation-wide surveys and modeling to calculate approximate FW quantities generated at households in their research, whereas Nahman et al. (2012) and Reynolds et al. (2014) aggregated data from several previous studies to obtain their estimates. This method is also appealing and applicable in instances where the access to primary data is limited or not available. Thirdly, this method usually covers a large sample size, often estimations for entire regions (e.g, EU) or countries (Nahman et al., 2012).

Table 9: Strengths and weaknesses of using secondary data as a method

Strengths	Weaknesses
• Beneficial when primary data is inaccessible [27, 28, 29 30, 33] • Can cover a large sample size [27, 28, 30, 32, 34] • Low cost and less arduous [30, 31, 33, 34]	• Highly impossible to collect accurate composition data [27, 30, 31, 32, 33, 34] • Accuracy depends on the approach [28, 29, 31, 32, 33, 34] • Cannot study root causes or food wasting behaviors [28, 29, 32, 34]

However, the data collection and analysis approach varies with each study and in turn so does the accuracy of resulting estimates (Caldeira et al., 2017). The data based on USDA loss adjusted FW and FAO regional estimates has been used repeatedly in FW research, although its applicability is questionable especially in the context of developing countries (Xue et al., 2017). Xue et al. (2017) argue that household waste statistics reported by FAO (2011) did not have a single measured data point in Asia or Africa. Thus, an inherent limitation in this method is the use of several assumptions and large approximations rather than precise quantification through measurement, which would result in FW estimates at household level with a significant margin of error. Further, the aggregation of results from different studies that have used different approaches can also increase the uncertainty of findings.

2.2.2.5 Mixed methods approach

The current review identified three studies (Group A in Table 10) that have compared two or more of the above methods and another eight studies (Group B in Table 10) that combined two or more of the above methods to estimate FW at households. Studies in Group A used two or more methods individually to quantify FW and then drew comparisons among the results, whereas studies in Group B present results based on a combination of multiple methods. A brief overview of these studies are given in table 10.

Using a mixed method approach can be beneficial since it can be designed in a way that strengths of one method would compensate for the weaknesses of the other, and to address data gaps from certain methods. For instance, when waste audits alone cannot observe the root causes and behavioral aspects associated with food wasting behaviors, this challenge could be overcome by coupling a waste audit with a follow up survey (Khalid et al., 2019; Rispo et al., 2015; Sosna et al., 2019).

Table 10: Overview of the studies that used more than one method

Article	Country	Approach
Group A - Comparison of methods		
Delley & Brunner (2018)	Switzerland	Postal survey results compared with extrapolated results from a national waste compositional analysis report
Giordano et al. (2018)	Italy	Survey followed by diary for one week, waste audit followed.
van Herpen et al. (2019)	The Netherlands	Compared general surveys, diaries, photo coding, kitchen caddies, and pre-announced survey questions regarding a specific time period. In an experiment, respondents were asked to assess their food waste using some or all of these methods depending on condition.
Group B - Studies that used multiple methods		
Khalid et al. (2019)	Pakistan	Waste audit (kitchen caddies) followed by a face to face interview
Koivupuro et al. (2012)	Finland	Kitchen diary coupled with a follow up survey
Parizeau et al. (2015)	Canada	Waste audit with a follow up survey
Rispo et al. (2015)	UK	Waste audit (bulk sampling at collection points) followed by a survey
Song et al. (2015)	China	Survey data coupled with existing Life Cycle Assessment data

Article	Country	Approach
Sosna et al. (2019)	Czech Republic	Waste audit combined with observations, informal interviews and semi standardized interviews
Urrutia et al. (2019)	Canada	FW measurement by researcher for quantification and participant observations and interview data to understand material and visceral dimensions of household FW
Xu et al. (2016)	China	Weekly waste audits followed up with a post program interview

2.5 Discussion

In this research, 45 studies using five different methods to quantify and analyze the composition of FW at household level were reviewed. Considering the strengths and limitations of each of the methods discussed in the previous sections, it is reasonable to argue that there is no 'one best' method for FW quantification at household level. However, selection of the most appropriate method should depend on the research question each study is trying to answer and the level of access to resources. Using the findings of the current review, we present a simple decision tree to guide future researchers to select the most appropriate household FW quantification method (Figure 6).

If the study objective is quantification rather than composition analysis, most accurate results can be obtained through a weight-based waste audit, given that the researcher has direct access and resources to collect and measure FW. For instance, many studies attempt to quantify household FW at municipal or provincial levels to assist in the policy and decision-making processes related to organic waste management; i.e., to establish or manage central composting facilities, to promote home composting, to increase waste diversion etc. For such requirements, estimating the quantity of FW as accurately as possible is more crucial than the exact composition, and a simple weight based audit would be most appropriate. A weight-based waste audit should focus on measuring the weight of FW in a larger sample (higher number of households) and might not need an in-depth composition analysis. In an instance where resources are limited and collecting FW from households is impossible, a kitchen diary method could be used. Although surveys can also estimate the quantities, accuracy would be lower since respondents are reporting quantities based on recall.

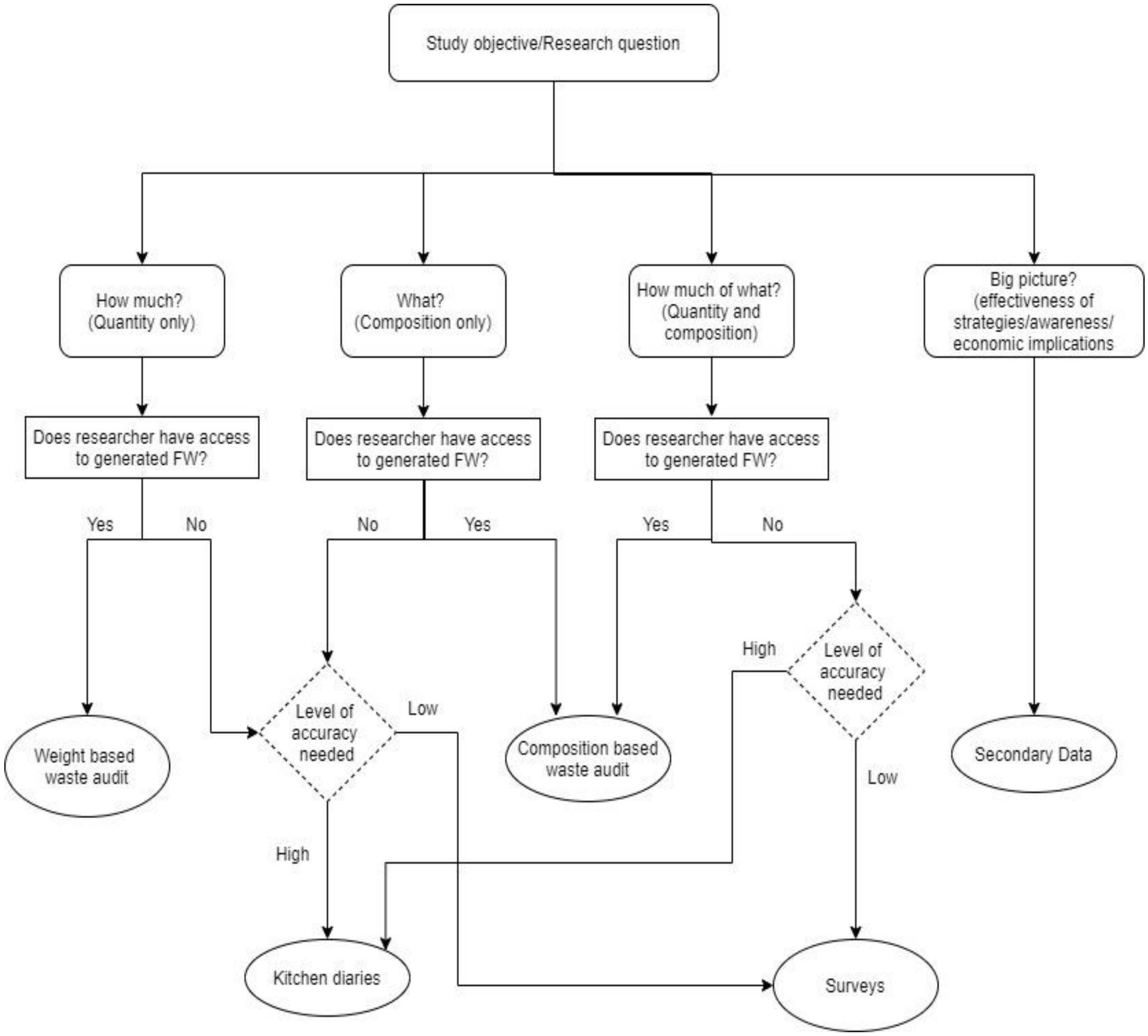

Figure 6: Simple decision tree to select appropriate household FW quantification methods.

Note that resources available (e.g. time, personnel) need to be factored in with respect to how many samples are needed.

For studies in which the research question is more biased towards composition than quantity, a composition-based waste audit could be carried out. In a composition-based waste audit, a researcher could focus more on categorizing FW into as many types as required (avoidable/unavoidable or according to type of food) in a smaller sample of households, in contrast to weight-based audits. Nevertheless, if access to collecting waste is restricted, the kitchen diary method could be designed to capture as much compositional data as required.

Similarly, studies that focus on life cycle aspects of food systems may require quantity of FW as well as composition. The best approach to capture both these parameters is to do a composition-based waste audit. Sample size should be decided based on the required accuracy and available resources. Although waste audits generate more accurate and representative data without inducing behavior change, audits are resource and cost intensive and require intense planning. Kitchen diaries can also be used to assess both quantity and composition at the same time by asking respondents to measure and record exact quantities and composition. However, there is a probability that response rate could decrease over time due to the significant effort needed from the respondents.

Due to the variability in study designs even within a single method, it is extremely difficult to draw a valid comparison among the quantities of household FW in two countries or regions. For instance, from the selected 14 studies (for the current review) that used waste audit as the primary method, eight studies reported FW as a per household value while six remaining studies reported it as a per capita value. As another example, while Parizeau et al. (2015) reported that the average organic waste production in Southern Ontario (Guelph) households to be 4.2 kg per capita per week, van der Werf et al. (2018) reported that the Southern Ontario households generate about 2.4 kg of organic waste per week. While Parizeau et al. (2015) conducted a waste audit in 222 households for a period of two weeks, van der Werf et al. (2018)

estimated the FW using waste audit data from approximately 900 households in nine municipalities over the period of four years. This illustrates how a particular study method and sampling approach can significantly impact the quality and comparability of results.

Another important factor is the ability of each method to analyze the composition of FW since it is highly important to know what is wasted in order to develop strategies aimed at FW reduction (van Herpen & van der Lans, 2019). Surveys and kitchen diaries can obtain detailed information about the types of food wasted. However, with surveys, respondents have to recall their food wasting incidents, and it is possible that people might not remember every food item they wasted. With kitchen diaries, if the respondents are asked to fill out the diaries at the time of waste generation, it is quite possible to capture more accurate information about the types of food wasted. Nevertheless, reluctance to record actual behavior can challenge the accuracy of the records. In contrast, the FW audits where the researcher could go through the waste collected at households, are able to generate more accurate findings regarding the composition of FW as well as the quantity of each waste fraction (Edjabou et al., 2018). Nevertheless, FW tends to decompose faster, especially in warm climates, making it hard to identify each fraction while sorting (Edjabou et al., 2018). This could be avoided by decreasing the time between waste generation and sorting (e.g., collecting waste samples daily or twice a week instead of weekly). Novel methods like photo coding and using fridge cameras can also generate comparatively accurate compositional data than surveys (van Herpen & van der Lans, 2019). Although coupling two or more methods in a single study would be able to eliminate the weaknesses of a single method, there is still a possibility that it might not be comparable with another study.

The most significant issue regarding FW composition analysis is the lack of an internationally accepted standard classification for types of FW. Although many studies follow the categorization introduced by WRAP by classifying FW into avoidable, possibly avoidable and unavoidable categories, the actual sorting of FW during the study depends on the perspective of the researcher or the participant. Due to cultural and societal perceptions, what people perceive as avoidable could be different from region to region. Researchers generally define the avoidability upon local understanding, making it fundamentally difficult for a meaningful comparison among studies in different geographical regions (Lebersorger & Schneider, 2011). Although defining a standard classification can enable meaningful comparison, it is also important to pay attention to local perceptions since the wasting behavior depends on the self-perception.

2.6 Conclusions

FW has become an environmental as well as a societal issue with a high impact in both developed and developing countries that has important policy implications. With households being the largest contributor to FW, especially in developed countries, valid measurements or quantifications of FW at households are important as they provide the opportunity to assess the nature of FW, to draw comparisons across time, countries/regions, and/or consumer groups, to examine causes of FW generation, and to assess the effectiveness of interventions.

This comprehensive review of recent studies (2010 To 2019) that quantified household FW analyzed the strengths and weaknesses of five different FW quantification methods and concluded that there is no ‘one best’ method for FW quantification at household level. Given the need to customize quantification methods based on the research question being asked, we provided a decision-tree to aid researchers in choosing a method. However, the notable issue with having such diverse array of methods is that the researchers are unable to compare the FW scenarios for two different geographical regions at a higher accuracy. Even the studies that used the same methods (e.g. surveys) generate results that are not quite comparable even with a similar study due to the vast differences in the protocols within the same methods (generating FW figures as percentage of consumption vs frequency). Thus, it is still important to develop standard protocols for each of these methods so that the researchers will have the ability to compare and contrast their findings with similar studies around the world. Nevertheless, it should be noted that the present study has few limitations in its approach towards literature review, where considering only one database “Scopus” is the major limitation. This review only looked at studies in which the main aim was to quantify and/or analyze composition of FW at households, and did not consider the studies that were aiming at studying the attitudes, beliefs and behaviors associated with FW or the studies that looked at all residual household waste in general without special emphasis on FW.

CHAPTER 3

Composition of Household Food Waste in the Region of Waterloo, Canada: A Pilot Study

3.1 Introduction

Food loss and waste that occur throughout the food supply chain (FSC) have adverse impacts not only on the environment, but also on the economy and society on a broader scale (Abdulla et al., 2013; Gooch & Felfel, 2014). One of the key approaches towards handling FW issues would be measuring, tracking and reporting the quantities and composition of waste generated across the FSC, as it is not possible to manage something that is not measured (Bellemare et al., 2017; Elimelech et al., 2018; Rajan et al., 2018). In Canada, nearly half of the avoidable FW is generated at households, and this waste has been valued to be $10.4 billion worth of food annually (Gooch & Nikkel, 2019). Thus, it is important to assess the quantity and composition of household FW in order to make informed policy decisions and implement interventions at residential level (von Massow et al., 2019). However, as most of the available studies that estimate FW quantities have used secondary data and aggregate data collected at municipal or national levels, there exists a huge research gap in assessing post-consumer FW at the household level (van der Werf et al., 2018; Xue et al., 2017).

With the recent increase in attention on FW in both research and policy sectors, several attempts have been made in Canada to quantify FW along the FSC. A recent study done by the Commission for Environmental Corporation (CEC) generated a comprehensive estimate for organic waste in Canada by extrapolating data from a limited number of composition audits from residential and industrial sectors (CEC, 2017). They reported that Canadian households waste 85 kg of FW per person annually (CEC, 2017). Gooch & Nikkel (2019) estimated that 35.5 million metric tons of food is lost or wasted in Canada which includes 11.2 million metric tons of avoidable FW. These estimates were based on surveys, interviews, and secondary data at different stages of the FSC, whereas household FW quantities were estimated using aggregate food availability data from Statistics Canada. While both these studies did not directly measure FW at the household level, two other studies (Parizeau et al., 2015; Urrutia et al., 2019; van der Werf et al., 2018) managed to quantify FW in southern Ontario households through composition audits.

In Canada, mostly municipalities or regional governments take initiatives in implementing intervention programs and introducing policy frameworks for consumer FW reduction at the local level. For example, some municipalities in Southern Ontario, such as York, London, and Guelph, have developed local communication campaigns and awareness raising programs for consumer FW reduction (Regional Municipality of York, 2019; van der Werf, 2018). For the effectiveness of such policy initiatives and interventions, it is crucial to understand the quantity and composition of FW generated in each sector, since evidence-based decisions can aim for tailor-made, action oriented interventions at municipal level.

Several such detailed observational studies for understanding household FW composition were carried out at the City of Guelph, Ontario recently. The study by von Massow et al. (2019) assessed household FW composition by auditing all waste streams (garbage, recycling and organic waste) from 94 families with young children in Guelph, Ontario. During this study, data on food purchases, food consumption, and waste generation were collected over multiple weeks to generate estimates on FW composition and associated economic losses, nutritional losses, and environmental impacts. Another study in Guelph, Ontario was carried out by the same research group to explore the association between diet quality and FW in Canadian families (Carroll et al., 2020), which also assessed the composition of FW generated at 85 households with young children. However, it should be emphasized that the generalizability of the results from the above two studies for other municipalities is limited due to several reasons. Firstly, City of Guelph has a generally more 'waste aware' community relative to other communities, due to active communications and educational programs, which may have resulted in greater understanding about FW in the households (Carroll et al., 2020; von Massow et al., 2019). Secondly, the voluntary nature of participation may also have incurred some bias since the sample could have been dominated by participants with pre-existing interests. Thirdly, both studies only focused on families with young children, which is not representative of the socio-demographic diversity of the municipality as a whole.

In the context of the Region of Waterloo, although the municipal government conducts routine waste audits that also include the organic waste stream in general, no recent and detailed granular data is available regarding the quantity or composition of FW at households in the Region. However, a study by Urrutia et al (2019) assessed the FW occurrences at 13 households in Waterloo using a mixed method approach that attempted at understanding the food wasting behaviors at households. During this study, participating households were given a "FW collection kit" along with a FW diary, to collect and record all FW during a week. Collected FW was audited by the researcher and coupled with the data collected through FW diaries and interviews. Although this study presented valuable insights into quantity and composition of FW in terms of avoidability, major limitations were the small sample size and the possibility of induced behavioral changes due to participants being aware of their FW being observed. Moreover, the above study was carried out in 2014 and with the recent attention on FW across the world, it is safe to assume that food wasting behaviors might have evolved during the last 5 years.

As repeatedly emphasized by Edjabou et al. (2016), Parizeau et al. (2015) and von Massow et al. (2019), municipalities can greatly benefit from detailed information regarding the quantity and composition of FW, especially at households, in order for the policy-makers to make informed and evidence-based decisions. Thus, considering the lack of detailed and up-to-date observations regarding household FW in the Region of Waterloo, it is important to conduct a composition audit to address the existing knowledge gaps.

As recommended by Parizeau, von Massow, & Martin (2015) and van der Werf, Seabrook, & Gilliland (2018), the current study is aimed at conducting weight-based waste audits to gain additional insights into the composition of household FW in the Region of Waterloo. As discussed previously in Chapter 2 waste audits are able to provide detailed information about FW composition without inducing behavior change in households. Although other FW quantification methods such as surveys or kitchen diaries are also capable of assessing FW composition, results could be less accurate as participants tend to lean towards 'socially desirable' responses (Martindale, 2014; Visschers et al., 2016). In contrast, results from waste audits, when carried out by an independent third party (researcher), are more accurate and objective (Edjabou et al., 2016; Parizeau et al., 2015, Withanage et al., 2020).

This study is aimed at analyzing the composition of green bin waste collected from residential areas of the Region of Waterloo. This will address some of the existing knowledge gaps on the composition of FW generation at Southern Ontario households. Additionally, the findings of the study will be inherently useful for life cycle material flow analysis of Canadian dietary patterns by contributing to the existing knowledge on waste-related behaviors at post-consumption stage. Most importantly, this study will provide preliminary baseline information regarding the current household level FW situation of the Region of Waterloo that could be used in implementing a Municipal FW Prevention program as recommended by Environment and Climate Change Canada (Environment and Climate Change Canada, 2019).

3.2.1 Research questions and objectives

The main objective of this study is to identify the composition of FW generated in the households in the Region of Waterloo. The specific research questions are:

1. What is the average composition of FW generated from households of the Region of Waterloo?
2. Which categories of food contribute mostly to the avoidable FW?

3.2 Methods

3.2.1 Background of the study context

The Region of Waterloo has a source-separated waste collection program in effect for all residential neighborhoods, where residents are encouraged to separate their household waste into organics, recyclables, yard waste and garbage. Organic waste should be sorted into a green bin, usually with a compostable liner in it, and is collected weekly at the curbside during the designated garbage collection day. The green bin liner, which is recommended but not required, could either be compostable green bin liners that are available in the market, or self-made paper liners. All compostable waste from the Region of Waterloo is sent to a composting facility in Guelph, ON, operated by the City of Guelph. Green bin waste collected from curbside is first transported into a holding facility in Waterloo, where it is stored for two to three days before being transported to the composting facility in Guelph.

3.2.2 Sample collection

For the pilot waste study, sample collection was done at the organic waste holding facility in Waterloo from the waste pile unloaded by the collection trucks between August 23rd to August 26th, 2019. A randomized grab sampling method, presented by Oelofse et al. (2018), was used for the current study, where 16 individual samples were collected along the face of the waste pile at the holding facility on August 27th, 2019. Since the majority of the waste was in compostable bags (instead of disposing FW without any bags), a single bag was considered as an individual sample.

The sampled green bin materials were collected by the municipal collection truck from curbsides of residential areas in the City of Waterloo during the weekly garbage collection. Thus, the samples contained organic material disposed throughout a week at households. A single bag of waste is considered as an individual sample in the current study. A major limitation researchers faced during the sample collection was the inability to link samples to their source. Since the samples were collected at the municipal collection facility, it was impossible to observe how many bags of waste a single household would dispose of during a week. Therefore, the results of the current study should be interpreted with caution. Although it is safe to assume that all material in a single bag represents waste generated in a single household, an individual sample might not be representative of the total weekly generation of FW in an individual household.

3.2.3 Sample Analysis

Each individual sample was weighed, and the wet weight was recorded before opening the bags to assess the composition. As the first step of the composition analysis, contents in the sample were sorted into two categories; FW and non-FW. As many compostable organic materials, such as kitchen napkins, paper, compostable food packaging and some garden waste, frequently get disposed of in the green bin, the sorting of FW from non-FW was essential. The sorted out fraction of FW in each sample was then subjected to further sorting according to the type of food. During this second sorting, the FW in each sample was sorted into 6 pre-defined categories (Figure 7), which were based on the classification previously introduced by Edjabou et al. (2016). FW in each category was weighed and recorded separately, and individual values were added to get the weight of total FW.

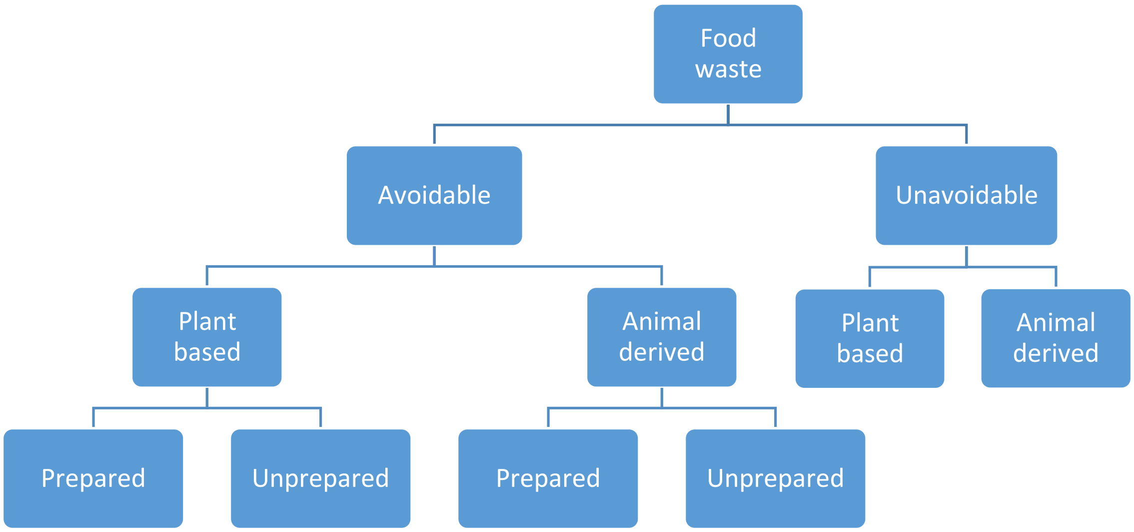

Figure 7: FW categorization used in the current study

As depicted in Figure 7, the categorization was based on three parameters; avoidability, food source, and level of preparation. Avoidability was decided based on whether or not the food would have been edible under normal circumstances. If the particular food item "is not and has not been edible under normal circumstances" (FUSIONS, 2014), it was categorized as 'unavoidable FW', whereas edible food "that could have been eaten but disposed regardless of the reason" (FUSIONS, 2014) were categorized as 'avoidable FW'. However, it is important to acknowledge that due to cultural and societal perceptions, what people perceive as edible could be different from region to region and also from one household to another. For example, some may discard apple skins and apple cores, whereas others may eat apples with the skins.

Some may discard broccoli stalks and only eat the florets, while some may eat the stalks too. While beet greens, potato and carrot skins are often discarded as inedible, it can be argued that they are edible if rightly prepared. However, for the current study, FW items were considered avoidable if a vast majority of Southern Ontarians would consider them edible.

The second tier in classification was based on whether the food originated from a plant-based or animal-derived source. In the third tier, avoidable FW was categorized into two further fractions. Food items "that have been cooked, prepared or served at home" (Edjabou et al., 2016b), were categorized as 'prepared' and "purchased food that has been discarded without being cooked, prepared or served as a meal" (Edjabou et al., 2016b) were categorized as 'unprepared'. In this study, industrially processed food items that have to be cooked at home to be served were also categorized as unprepared, if they were not cooked at home (e.g. processed meat discarded without being cooked or prepared for a meal at home). As a result, the current study used the following six detailed FW fractions,

1. Unavoidable Plant Based (U-PB)
2. Unavoidable Animal Derived (U-AD)
3. Avoidable Prepared Plant Based (AP-PB)
4. Avoidable Prepared Animal Derived (AP-AD)
5. Avoidable Unprepared Plant Based (AU-PB)
6. Avoidable Unprepared Animal Derived (AU-AD)

Once the sorting was completed for an individual sample, each fraction of FW was weighed using a laboratory scale (accuracy = 0.0001 kg), and the wet weight was recorded. Due to decomposition of FW, there was a fraction of material that was unidentifiable. This fraction was weighed and recorded separately as 'Other'. In addition to the wet weight, descriptive information and photographs were recorded for each sample.

3.2.4 Data analysis

All non-food materials such as kitchen napkins, tissue papers and paper food packaging were removed from each sample before sorting FW into the previously-mentioned categories. Such non-food material was found in thirteen out of sixteen samples analyzed. Composition analysis and the calculation of the proportions of avoidable, unavoidable and unidentified FW were carried out after removing the non-food material, and they are presented as a percentage of total FW, instead of total organics.

3.2 Results

The current study presents data from analyzing 16 individual samples of green bin waste material collected at the Municipal Waste Collection Facility in the Region of Waterloo during the Summer of 2019. A total of 25.54 kg of FW was analyzed after removing non-food material. With further sorting, 10.9 kg of FW was identified as avoidable, which accounts for 43% of the total FW (Figure 8). The weight of total unavoidable FW was 9.14 kg, making up 36% of total FW in green bins.

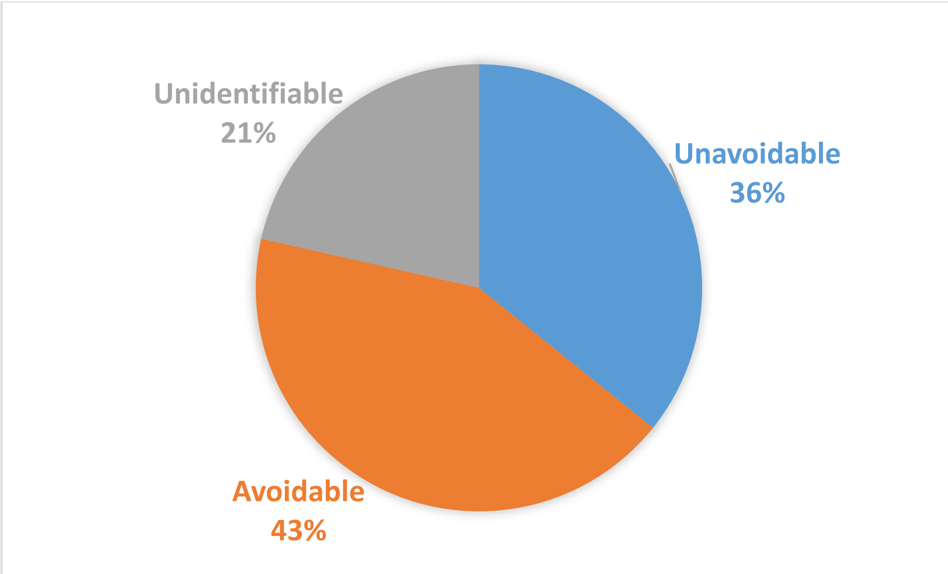

Figure 8: Average composition of FW analyzed in the present study.

Approximately 19% of the green bin waste material was in an unidentifiable stage due to decomposition and compaction. As the sample collection was done in late summer, high air temperature may have resulted in this quick decomposition of FW (average temperature for the week of August 20th to 26th 2019 fluctuated from 22.6 ^{o}C to 29.3 ^{o}C according to The Weather Network (2020)). Moreover, since the municipal waste collection happened weekly, the analyzed samples could contain FW that was 2 to 7 days old. In addition, the conditions inside the collection truck might also have resulted in further compaction of FW.

3.2.1 Composition analysis of individual FW samples

The total weight of individual samples ranged from 0.93 kg to 2.86 kg. Average composition of FW assessed in the present study is illustrated in Figure 9.

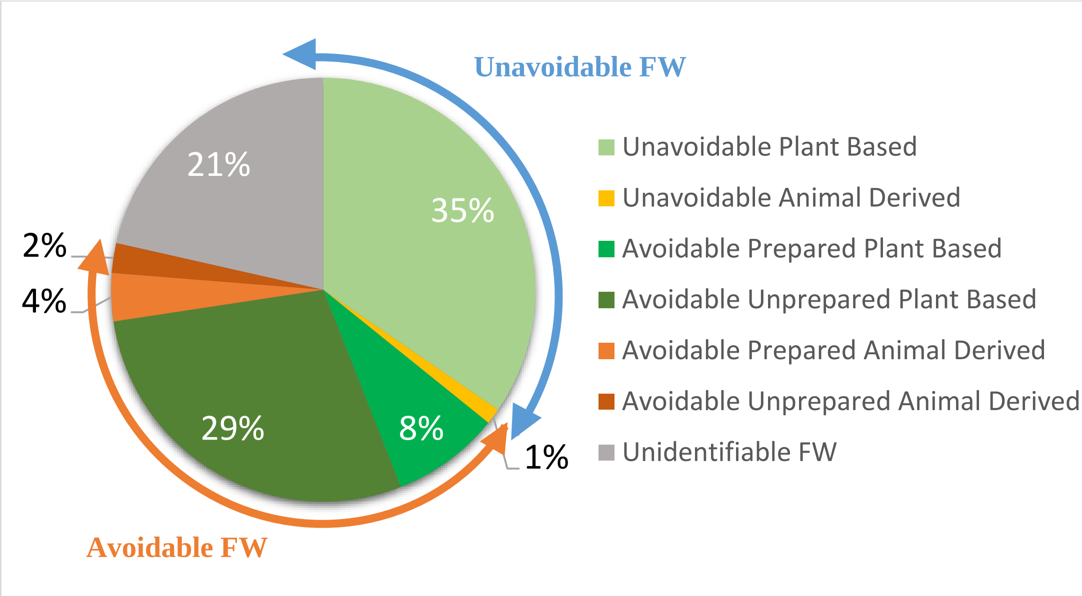

Figure 9: Average composition of FW in 16 samples.

3.2.1.1 Details of unavoidable FW

From the total mass of 25.54 kg of FW, 9.14 kg (or ~36% of total FW) was unavoidable, with 8.83 out of 9.14 kg being plant-based, making up 96.6% of all unavoidable FW, and 35% of the total FW. This category was mainly composed of inedible fruit and vegetable peels generated at the meal preparation stage (Figure 10). Banana peels, orange peels, watermelon rinds, and vegetable peels discarded during meal preparation, were some of the more frequently observed unavoidable plant based FW. The percentage of unavoidable animal-derived FW was only 3.4% of the total unavoidable FW and 1% of the total FW (0.3 kg in total). This category was mainly comprised of meat bones and egg shells. Unavoidable plant-based FW was present in all samples, except for sample 8, making this category the most frequently occurring type of FW (Figure 11). Unavoidable animal-derived FW was found in minor quantities in only seven out of the sixteen samples.

Category	Examples	
Unavoidable	 Plant Based (U-PB)	 Animal Derived (U-AD)
Avoidable Plant Based	 Prepared (AP-PB)	 Unprepared (AU-PB)
Avoidable Animal Derived	 Prepared (AP-AD)	 Unprepared (AU-AD)

Figure 10: Examples for each category of FW observed in the current study for the six categories; unavoidable plant-based (U-PB), unavoidable animal-derived (U-AD), avoidable prepared plant-based (AP-PB), avoidable unprepared plant-based (AU-PB), avoidable prepared animal-derived (AP-AD), avoidable unprepared animal-derived (AU-AD).

3.2.1.2 Details of avoidable FW

Avoidable FW contributed to 43% of the total FW with 38% being plant-based and 5% being animal-derived. From 9.4 kg of avoidable plant-based FW, 2.1 kg could be identified as prepared/cooked at home for a meal. This avoidable prepared plant-based FW, such as baked products served at home (e.g. sandwiches), cooked rice and cooked vegetables, contributed to only 8% of the total FW.

There were 7.3 kg of avoidable unprepared plant-based FW, which contributed to 29% of the total FW. This category was mainly comprised of fresh fruits and vegetables that were not cooked or prepared for a meal at home. Apples, tangerines, corn on cobs, lettuce, and potatoes, are some of the examples of unprepared plant-based FW found in the samples. The higher percentage of fresh fruits and vegetables could be correlated to the seasonal availability since the study was done in the summer. Seasonal produce, such as corn on the cob, is much more popular in the summer due to its availability.

As depicted in Figure 11, avoidable plant-based FW was found in 13 of the 16 samples, suggesting that the majority of households generate at least some amount of avoidable plant-based FW. In 10 of these 13 samples, the quantity of unprepared FW is much higher than the quantity of prepared FW, indicating that fresh produce gets wasted more frequently and in larger fractions. This evidence suggests that the avoidable fraction of household FW is dominated by plant-based FW which could be highlighted as one of the key findings of the current study.

The total weight of avoidable animal-derived FW found in the present study was 1.52 kg. This accounted for 6% of total FW, 4% of prepared FW, and 2% of unprepared FW. Prepared animal-derived FW was observed only in four samples (Figure 11), which mainly had cooked eggs, sausages and meat. Sample 11 had two cooked eggs and several cooked sausages, making it the sample with highest amount of prepared animal-derived FW. It is possible that these originated from a family event or a barbeque, which are common occurrences in summer. Avoidable unprepared animal-derived FW was found only in one sample, which was an uncooked piece of ham.

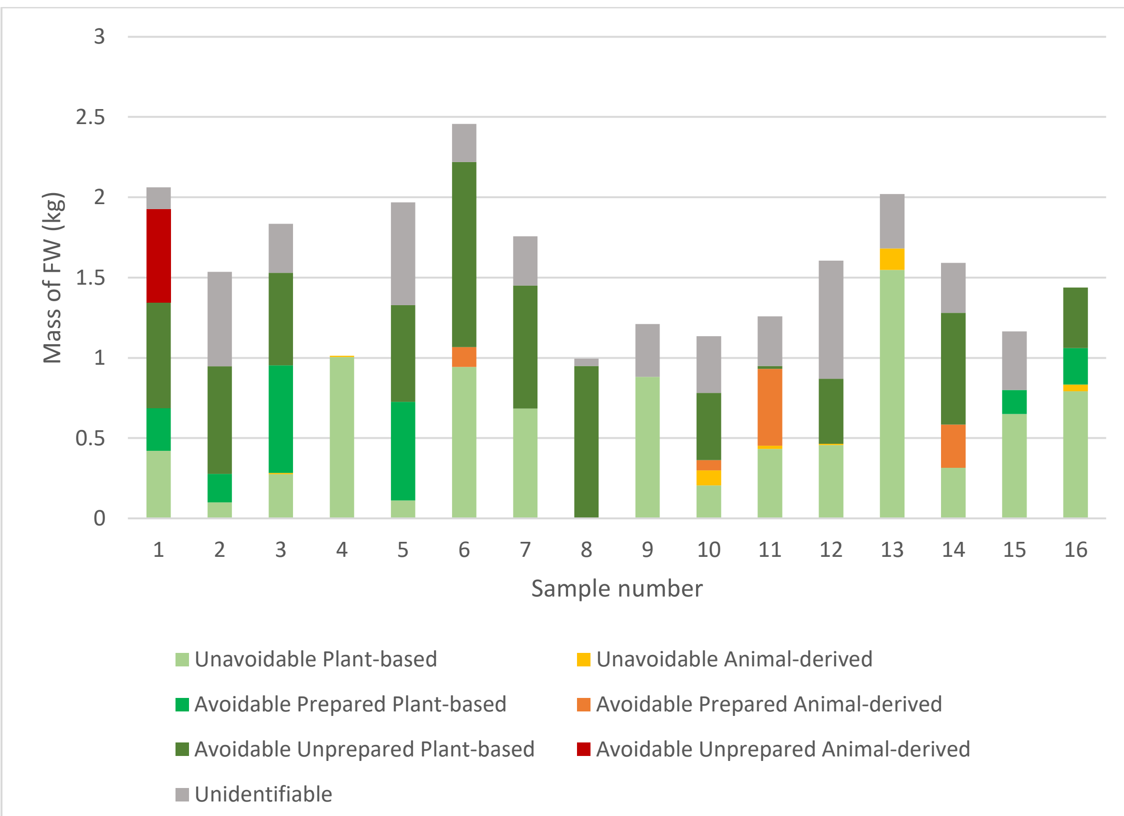

Figure 11: Composition of FW in individual samples (see Appendix 1 for details)

3.2.1.3 Composition of individual samples

As illustrated in Figure 11, the total weight of individual samples ranged from 0.93 kg to 2.86 kg. If it is assumed that each sample is representative of the weekly generation of FW in a single household, the average FW quantity could be 1.59 kg/household/week. However, this assumption is debatable since it is highly likely that a single household may dispose more than one bag of green bin waste per week. The distribution of weight and composition in individual samples further support this argument. Sample 6 had the highest amount of FW (2.86 kg) with 0.94 kg of unavoidable FW and 1.27 kg of avoidable FW. Interestingly, this sample comprised of a few distinct items, barbequed corn cobs, watermelon rinds and some cooked meat with some unidentifiable FW. This indicates that contents in this particular sample originated possibly from a barbeque event, and is not representative of all FW generated in the particular household. Similarly, the smallest sample was sample 8, weighing 0.93 kg, that contained only a few boiled corn cobs and an avocado in addition to some unidentifiable FW. This suggests that individual samples are not representative of the total weekly FW generation per household, which is a major limitation of the current study.

3.3 Discussion

3.3.1 General composition of household FW

A number of prior studies (Gooch & Nikkel, 2019; Parizeau et al., 2015; van der Werf et al., 2018) that assessed household FW in Canada have noted the importance of getting a better understanding of household FW composition so as to enable informed and evidence-based policy decisions and to implement effective FW reduction interventions at local level. The current study addressed this by conducting a weight-based waste audit of a sample of the municipal organic waste stream in the Region of Waterloo.

The average weight of samples observed in the current study was 1.59 kg. This is notably lower than the values reported from the previous study by Urrutia et al. (2019) in which the weekly generation of FW was observed to be 2.22 kg per household. A recent study in Guelph, reported that the average FW generation per household per week was 4.4 kg (von Massow et al., 2019). This indicates that individual samples considered in the present study are not representative of the total weekly FW generation in a household. Although the findings of this study are not representative of all households in the Region due to the small sample size, this study provided some insights into seasonal FW composition in households.

The first question in this study sought to determine the average composition of FW generated in the households of the Region of Waterloo. According to the findings, 21% of the FW was unidentifiable due to decomposition, with the remaining fraction consisting of 43% avoidable and 36% unavoidable FW. If the identifiable fraction of FW is considered exclusively, the percentage of avoidable and unavoidable FW is 54.4% and 45.6%, respectively. These results are relatively similar to the findings from an earlier study in Waterloo, which reported that 44.7% of household FW is avoidable and an additional 14% is possibly avoidable (Urrutia, 2014). These findings are also consistent with several other studies reporting avoidable waste on the order of 55% of total household FW (i.e. Edjabou et al. (2016) for Danish households; (Lebersorger & Schneider, 2011 for Austrian households; (Elimelech et al., 2018) for Israeli households). This suggests that despite the small sample, the composition analysis has captured similar trends of FW generation as many previous studies.

The second research question of the present study aimed to identify the categories of food that contributed the most to the avoidable fraction of household FW. Findings indicate that unprepared plant-based food items contribute to more than 67% of avoidable FW in Waterloo households. Accordingly, fresh fruits and vegetables could be identified as the most frequently wasted food category which also corroborates the findings from Edjabou et al. (2016) and Elimelech et al. (2018). In Danish households, 71% of total avoidable FW consisted of vegetable/fruit products (Edjabou et al., 2016), whereas in Israel it was 67% (Elimelech et al., 2018). A possible explanation for this high wastage of fresh produce could be inefficient purchase and meal planning that results in buying excessive amounts of fresh fruits and vegetables that could not be consumed before they perish (Edjabou et al., 2016; FUSIONS, 2014; Parizeau et al., 2015). In addition, improper storage could also result in higher wastage. Thus, for the Region of Waterloo, it could be suggested that responsible shopping behaviors, proper meal planning and correct storage might reduce the generation of avoidable FW in households substantially.

Moreover, it should not be ruled out that FW generation can be highly dependent on the season. This study was carried out at the end of summer, and there was evidence that some of the FW may have been generated following barbeque get-togethers and special occasions, where family and friends come over for meals. It is also possible that families are away more in the summer, at cottages, or camping, and this could affect the amount of FW at the household during that particular week, in one of two ways: less waste because the waste is happening elsewhere, or more waste because food may be purchased as if for a regular week, but then not eaten or prepared when people go on vacation. It has been note that food wasting patterns at households could drastically change with special life events, changes in routine, social gatherings and holidays or vacation plans (Evans & Siemens, 2016). To capture these variations due to season and special events, waste audits should be replicated over different seasons and following special holidays. This is particularly important as education and other interventions need to account for these changes in routine.

It is interesting to note that the presence of avoidable or unavoidable animal-based FW was comparatively low in the present study, making up only 6% of the total FW. This trend was observed in a number of previous studies. A study done in the UK in 2008 reported that meat and fish waste accounted for only 8.4% of total FW and 6.8% of all avoidable FW in UK households (Ventour, 2008). von Massow et al. (2019) reported that meat and fish made up approximately 6% of avoidable FW in Guelph households. In contrast, Edjabou et al. (2016) found that animal-derived FW was 29% of all FW. The reason for low amounts of avoidable animal-derived FW needs more investigation, but Ventour (2008) suggests that wastage could be proportional to consumption. UK consumers purchased 148 kg of vegetables, fruits and salads where as they only purchased 46 kg of meat and fish products per person per year (Ventour, 2008), representing ~24% of the combined weights of these foods. Nevertheless, there could be other reasons why households waste less amount of meat/fish as opposed to fruits and vegetables. For instance, people might tend to eat the meat and not waste it because they like it better, or because meat is more expensive. It is also possible that the green bin waste sampled for this study originated from a higher income neighborhood, where the households would purchase better quality meat, generating less waste. In addition, longer shelf life of animal-based products may also result in lower perishability, thus, lower wastage. However, it should be noted that more detailed behavioral studies are needed to clearly understand these findings.

An interesting observation from the present study was that only one sample contained unprepared animal-derived FW, which was one large unprepared portion of ham, which at 0.580 kg, accounted for more than $1/3^{rd}$ of the total avoidable waste in that specific sample. Moreover, another sample contained 0.479 kg of prepared animal-derived FW making up more than 96% of the avoidable FW in the sample. Although a single observation should not be used to arrive at conclusions, we cannot rule out the possibility that animal-derived FW could be generated in somewhat larger quantities in certain instances such as family gatherings. This indicates that although the frequency of generation of avoidable animal-derived FW is lower than its plant-based counterpart, the quantities could still be significant in the instances they occur. Some examples for such instances could be summer get-togethers, barbeque parties and camping trips where wastage could have occurred either due to people going away and forgetting the food they purchased, or due to a large number of guests contributing to more animal-derived waste (partially-eaten burgers, sausages, etc. due to large amounts of food served). Thus, more research is needed with larger samples, throughout different seasons and around special occasions to obtain insights into how people waste differently under different circumstances.

Findings from the current study are more valuable to understand the overall composition of household FW as opposed to the exact quantity and composition for individual households. According to the results, unavoidable FW in households is predominantly plant based. It is interesting to observe that three samples did not have any avoidable FW that could be identified. More than 75% of the content in all these three samples was plant based FW made up of meal preparation waste and fruit and vegetable peels. However, two of the three samples contained some unidentifiable waste that might have been cooked/prepared food which could have been avoidable.

Another interesting observation from the current study is that plant-based FW was available in all the samples, making up the highest percentage in each sample. This rules out the possibility of having home composting in any of these households, since none of the plant-based FW would be discarded in the green bin if the households had home composting.

In summary, the findings of this study indicate that a significant fraction (43%) of FW generated in households is avoidable and that more than 86% of this avoidable FW is generated from plant based food items. Interestingly, fresh produce that has been purchased and thrown away without even being prepared into a meal accounts for approximately 67% of the total avoidable FW at households.

3.3.2 Limitations and directions for future research

There are several drawbacks of using waste audits to analyze the composition of FW. Most importantly, waste audits are not capable of capturing FW disposed via alternative channels, such as home composting and pet feed. Moreover, it is possible that expired food with packaging ends up in the mixed garbage stream instead of in the organics (i.e. green) bin. Analyzing only the green bin waste stream is one of the major limitations of the current study. To eliminate the underestimation that might have resulted from this, future research should attempt to analyze samples from mixed waste stream as well.

Decomposition of FW due to aging and compaction has made accurate sorting quite difficult resulting in 21% unidentifiable waste. This is another major limitation that needs to be addressed in future research. Collecting green bin waste samples at the curbside instead of the collection point may eliminate the effect of compaction, while collecting samples daily or multiple times a week instead of weekly might help researchers identify and sort FW more accurately.

Findings of the current study cannot be extrapolated statistically to be representative of the entire Region of Waterloo due to the small sample size. Also, the findings do not indicate the quantity of FW generated in a typical household per week, or any correlation between household characteristics (i.e., income, household size) and the FW generation. Since this was a pilot study, this aimed to lay the foundation for a more detailed study by identifying the general composition of FW. For a more comprehensive study, it is recommended to use a different sampling method from randomized grab sampling at the collection point, preferably a method that could link individual samples to specific households. For example, collecting samples at curb side during the weekly garbage collection day would provide opportunity for exciting research connecting FW to its source. This would also generate more accurate results regarding individual household FW generation.

Finally, it is important to do more seasonal studies to understand how the FW generation changes according to the seasonal consumption patterns. Designing the studies around special occasions such as Christmas, Thanksgiving and other national holidays might also provide valuable insights into the variations in the quantity and composition of FW, and allow for better design of intervention programs to reduce household FW.

3.4 Conclusion

Composition analysis of household FW is highly complicated and challenging due to the level of effort needed for sample collection and analysis. The present study provided general composition of FW generated at household level in the Region of Waterloo. Similar to other studies, the results demonstrated that avoidable fraction is higher than the unavoidable fraction of FW, and that plant-based food items dominate the avoidable fraction. There was also evidence of the effects of seasonal and special events on FW generation. It could be suggested that measures to reduce wastage of fresh fruits and vegetables can significantly reduce the generation of FW in households, but further research is needed to quantify household FW during different seasons and holidays.

CHAPTER 4

Life cycle assessment of fresh and frozen broccoli produced and consumed in Ontario: Accounting for waste in the supply chain

4.1 Introduction

Fresh fruits and vegetables account for a significant proportion of avoidable FW at households (AlMaliky & AlKhayat, 2012; Bernstad, 2014; Edjabou et al., 2016b; Elimelech et al., 2018). Edjabou et al. (2016) reported that 71% of the avoidable FW at Danish households consisted of vegetable products, which amounted to 73 ± 8 kg per household per year. Similarly, fruits and vegetables accounted for 67% of avoidable FW in Israel households according to a study by Elimelech et al. (2018). Furthermore, results of the pilot household FW audit carried out in Waterloo in August 2019 (Chapter 3) indicate that fresh fruits and vegetables account for about 67% of the total avoidable FW in households in the Region of Waterloo.

Large fractions of fresh produce in household FW indicate that fruits and vegetables often get purchased and then thrown away, without having been cooked, prepared or served as a meal (Edjabou et al., 2016b). This could be mainly due to inefficient purchase planning and improper storage causing unnecessary and excessive food that neither could be eaten nor preserved for a longer period (K. Parizeau et al., 2015; Silvennoinen et al., 2014; Urrutia et al., 2019). This is more prominent in certain fruits and vegetables where the regular portion size available for purchase is usually larger than the quantity needed for a single meal. Some suggest that frozen vegetables could be an alternative to reducing FW at households due to excessive purchase of fresh produce, since frozen produce have a longer shelf-life (Janssen et al., 2017; Martindale & Schiebel, 2017).

Certain studies suggest that shifting from fresh to frozen produce can significantly reduce the FW generation at households (Janssen et al., 2017; Martindale, 2014). A study done in UK reported that 47 per cent less frozen foods is wasted as compared to fresh foods in typical UK households (Martindale, 2014). Janssen et al. (2017) compared FW from a number of fresh and frozen food equivalents, and observed that a smaller amount of frozen food was wasted compared to their fresh equivalents. Thus, it is important to consider greater utilization of food through frozen preservation, as a potential alternative to reducing household FW.

Although primary production (animal farming) generally constitutes the major percentage of environmental impacts in animal-derived food products, the post-harvest activities of vegetables, such as processing, transportation, packaging, and FW carry a significant environmental burden (Gustavsson et al., 2011; Sala et al., 2017). Accordingly, this suggests that different processing and storage methods, such as freezing of vegetables, can have a different environmental impact over the life cycle of the product. Although frozen vegetables can reduce the overall environmental impacts of FW relative to fresh vegetables, it is worthwhile to assess if it offsets the impacts due to additional processing and packaging. Thus, a comparison of life-cycle environmental impacts of frozen and fresh vegetables is important to provide evidence on what actions can be taken to reduce impacts in the food chain.

There have been few LCA studies comparing impacts of fresh and frozen fruits and vegetables, which also account for waste. An LCA for domestic and imported vegetables was done in United Kingdom (UK) in 2008, which covered frozen and fresh broccoli, salad crops and green vegetables (Canals et al., 2008). This study assessed a number of impact categories, and showed that while agricultural production carried the highest environmental burden regarding acidification, eutrophication and soil quality impacts, consumer stage (cooking and home preparation of food) accounts for the major proportion of climate change impacts due to energy use (Canals et al., 2008). Their findings suggest that fresh broccoli has comparatively lower environmental impacts than frozen broccoli, taking into account the FL and FW generated along the life cycle. Another study done in the USA compared life cycle environmental impacts of fresh imported and frozen domestic organic blueberries and found that imported fresh blueberries were more sustainable (Chapa et al., 2019). In the frozen blueberry life-cycle, agricultural production, processing, and transportation stages were the hotspots (Chapa et al., 2019). Although FW generation aspects of blueberries are different from that of broccoli, how environmental impacts change with processing and packaging, frozen transportation and retail storage could be similar in both products.

The goal of this study was to compare the life cycle environmental impacts of fresh and frozen produce. Taking into account the data availability and complexity, it is sensible to conduct a life cycle assessment (LCA) to quantify the environmental impacts of a single vegetable, rather than all vegetables in general. Although Canals et al. (2008) have already done a similar study, there is a need to understand the impacts based on region-specific FLW, agricultural practices and yields, and energy use. Broccoli is among the most popular frozen vegetables in the Ontario market, but it has recently been facing price fluctuations (Charlebois et al., 2019), having seen the highest price increase of 20.4% in 2017, amongst all vegetables in Canada (Agriculture and Agri-Food Canada, 2018). According to the crop profile of Brassica vegetables in Canada for 2015, 42% of broccoli consumed in Canada is grown in Ontario. Thus, broccoli was selected as the case study vegetable to compare the environmental impacts of frozen and fresh produce (Agriculture and Agrifood Canada, 2015).

Broccoli has received considerable attention over the last few years as a health promoting food that is beneficial for prevention of chronic cardio-vascular disorders and cancer due to its high content of bio-active phytochemicals and nutrients (Domínguez-Perles et al., 2010). However, due to the nature of the broccoli plant, which is made up of florets and a lot of leaves, the marketable florets portion represent only about 25% of aboveground biomass, producing a considerably high amount of wastage in agricultural production. Abnormal temperatures in the growing season can also result in significant losses in marketable yields (Domínguez-Perles et al., 2010). In addition, industrial processing of broccoli also produces a large amount of by-products including leaves, stems and florets that do not meet the marketable quality (M. Thomas et al., 2018). Although a small fraction of these by-products is used as forage, the rest is usually discarded. Due to the nutrient rich nature of broccoli, industry is exploring the possibility of using the discarded broccoli by-products as sources of nutrients giving opportunity for value-added products (Domínguez-Perles et al., 2010; Duarte-Vázquez et al., 2007; M. Thomas et al., 2018).

According to current market trends, fresh broccoli is sold only as full florets and consumers tend to only use the florets and not the stalks generating a lot of FW along the supply chain. When processing frozen broccoli, food processors are interested in maximizing the use of the plant, thereby reducing the amount of FW. Thus, broccoli provides an interesting starting point to assess whether the reduced waste is sufficient to offset the impacts due to freezing vegetables.

4.1.1 Goal and Scope

4.1.1.1 Goal of the study

The main goal of this study is to compare the life cycle environmental impacts of frozen and fresh broccoli produced and consumed in Ontario, so as to evaluate how the environmental impacts fluctuate with the differences in the amount of lost or wasted food, and the use of packaging in fresh and frozen broccoli. Different waste treatment scenarios are analyzed with reference to frozen and fresh broccoli supply chains to reflect real-life scenarios. Basically, this aims at identifying the hotspots in the broccoli life cycle, so that future studies can focus on specific product improvements based on the hotspots. Furthermore, this is a comparative LCA between the two broccoli processing methods, fresh and frozen, which attempts to understand whether the avoided FW in frozen broccoli life cycle is sufficient to offset the impacts due to freezing.

The results of this LCA are intended to provide direction for the vegetable industry to focus on key drivers of environmental impacts in production and processing of broccoli. This will aid in identifying the key impact areas that future research should focus on.

4.1.1.2 Functional Unit

As a vegetable, the main function of broccoli is providing nutrition. However, there exists no scientific evidence demonstrating that the nutritional content of frozen broccoli is significantly different than fresh broccoli. Assuming that the nutritional value of both fresh and frozen broccoli is similar, a weight-based measure is found to be more appropriate as the functional unit. Thus, the functional unit of the current LCA is '**one kg of consumed broccoli**'. Using a weight-based functional unit allows life cycle impacts to be calculated per unit of calorific value of frozen and fresh broccoli if needed, at a point where nutritional information becomes available. Moreover, a kg of 'consumed' broccoli is defined as the functional unit rather than a kg of 'purchased' or 'produced' broccoli, in order to capture the environmental impacts of food loss and waste from farm to fork.

The reference flow of either fresh or frozen broccoli will include the quantity of fresh broccoli needed to supply 1 kg of consumed fresh/frozen broccoli respectively. Based on the evidence from previous studies (Janssen et al., 2017; Martindale & Schiebel, 2017) it is hypothesized that the food loss associated with fresh broccoli is higher than that of frozen broccoli. FL and FW at each stage were estimated based on the findings from Canals et al. (2008) and Gooch and Nikkel (2019). Thus, the quantity of fresh broccoli needed to be produced in order to consume 1 kg of fresh broccoli would be higher than the quantity needed to consume 1 kg of frozen broccoli. All environmental impacts, including transportation and packaging from farm to fork, will be referenced to the quantities required to supply a kg of consumed broccoli.

4.1.1.3 Product system description

a. Frozen broccoli supply chain

This study aims to capture all environmental impacts associated with frozen broccoli from agricultural production to final consumption and disposal. The life cycle of broccoli is divided into five main stages, i.e., agricultural production, processing, regional storage and distribution, retail, and final consumption. Waste management was modeled separately at each stage to incorporate the impacts due to FW. The agricultural production stage includes all environmental impacts due to soil preparation, planting, fertilizer use, irrigation, pest and disease management, and harvesting. This process was modeled based on the data from Stoessel et al. (2012), where the crop cycle was 2.1 months and the yield was 17 t/ha. Electricity usage was modeled to represent the Ontario electricity grid. Since the yield represents the marketable harvest, excluding the waste, FL at the field was not incorporated into the model separately. Moreover, as the forage and non-marketable florets are left on the field after harvesting the marketable florets, no separate waste treatment was considered at the agricultural production stage.

The processing stage captures the initial washing of broccoli, cutting, freezing, and packaging. Input flow data was obtained from a study (Canals et al., 2008) that assessed a large scale vegetable freezing farm in the United Kingdom (UK), where detailed data were gathered for the full operation of the plant, which included washing and packaging of the vegetables. Hence, aggregated data on input flows per kg of total processed and packaged produce was used in the study, assuming this value is representative for each type of vegetable, including broccoli. Amount of plastic packaging and cardboard boxes used are also considered and included in the processing stage. Due to the limited availability of data for food loss estimates during broccoli processing for Canada, data from a UK broccoli processing facility was used to calculate the output flows and percentage loss per kg of packaged produce.

Transportation from processing facilities to Regional Distribution Centers and storage at these distribution centers were considered as the next stage and modeled separately as an individual unit process. At the retail stage, transport from regional distribution centers to retail stores and retail storage are assessed. Energy usage data was obtained from Canals et al. (2008) where storage duration in regional distribution centers and retail were estimated based on the supply chain information and shelf-life of frozen broccoli in UK. However, energy usage was modeled to be representative of the Ontario electricity grid. At the retail stage, food loss estimates for frozen broccoli were calculated based on Canals et al. (2008) and (Gooch & Nikkel, 2019).

The final stage of the frozen broccoli supply chain is consumption at households including the treatment of FW generated at households. This study only considered home consumption, thus is not representative of broccoli purchased and consumed in the food service sector (e.g.

restaurants). The final consumption stage included in-home storage, cooking and preparation, and FW at households.

Treatment of FW and packaging waste was incorporated into each life-cycle stage. The study attempted to reflect real-life waste treatment and disposal scenarios in Ontario by using a combined approach of landfilling and composting. According to the Food and Organic Waste Framework of Ontario, only 25% of organic waste from Industrial, Commercial, and Institutional Sector (IC&I) gets diverted into waste recovery pathways (i.e., composting, anaerobic digestion), while 75% of organic waste still ends up at disposal sites, specifically landfills. In the residential sector, the diversion rate is a little higher with 50% of organics being sent to waste recovery facilities, specifically for composting (Government of Ontario, 2018). Considering these percentages, it was assumed that 75% of FW generated at the processing facility in the frozen broccoli supply chain was landfilled, while the remaining 25% was composted. Given that frozen broccoli comes in individual packaging and it is highly unlikely that the retailer would separate the FW from packaging to compost the FW, it was assumed that all FW from frozen broccoli would be landfilled at the retail stage. Considering the residential organic waste diversion rate, it was assumed that 50% of FW generated at the households was composted and 50% was landfilled. All packaging waste throughout the supply chain was assumed to be landfilled.

b. Fresh broccoli supply chain.

Both frozen and fresh broccoli are assumed to be produced in the same way on the farm. For the fresh produce, processing stage only includes washing, initial cooling to reduce field temperatures, and packaging. The amount of packaging material used for fresh broccoli is considered to be lower than for frozen broccoli (Canals et al. 2008), as fresh broccoli is usually sold lose, as single florets, whereas frozen broccoli is usually sold in individual packages that contain cut broccoli pieces. The packaging for fresh broccoli includes mostly the bulk packaging (large cardboard boxes) used for transporting fresh produce from processing farms to regional distributors and then to retailers. Other than that, it is assumed that per one kg of fresh broccoli purchased, one plastic bag would be used by consumers during grocery shopping. Although consumers may use a second plastic bag or a reusable shopping bag to hold all the groceries together, that second bag was excluded from the product boundary during this study. In the consumption stage, home storage, cooking and FW at households are considered for the fresh broccoli supply chain as well as the transportation of waste to waste treatment facilities.

4.1.1.4 Alternative Scenarios

Considering the availability of various treatment methods that can be utilized to treat FW, it is important to ascertain the associated environmental impacts of these methods, especially to make informed waste management decisions. Some commonly used FW management/ treatment methods are composting, anaerobic digestion, landfilling, incineration, or diversion to animal feed (Al-Rumaihi et al., 2020). According to Ontario's Food and Organic Waste Framework, the province has regulatory approaches in place to ensure resource recovery by utilizing either composting or anaerobic digestion to treat FW (Government of Ontario, 2018). Although composting is the primary FW treatment method currently in place in many Ontario municipalities (Government of Ontario, 2018), it is worthwhile to assess how the environmental impacts change if FW was treated by both composting and anaerobic digestion. Thus, in the current LCA, two scenario analysis were carried out considering either composting or anaerobic digestion as the primary FW treatment option assuming 100% organic waste diversion.

In scenario A, all FW at processing and households in the frozen broccoli supply chain was assumed to be composted while FW at retail was still landfilled due to presence of individual packaging. For fresh broccoli, all FW along the supply chain was assumed to be composted. For scenario B, instead of composting, anaerobic digestion was used as the primary waste treatment method. It was assumed that all FW from fresh and frozen broccoli supply chains were sent to anaerobic digestion except for the frozen broccoli waste generated at retail, which was landfilled. However, it should be noted that in both scenarios, composting and anaerobic digestion were modeled as waste treatment methods independent from the product system in the current LCA and not as a system expansion, thus credits due to nutrient recovery, production of heat or electricity are not integrated into the system. The major differences between fresh and frozen broccoli supply chains in the default and alternative scenarios are summarized in Table 11.

Table 11: Main differences between frozen and fresh broccoli supply chains in the default and alternative scenarios *(Packaging waste was assumed to be landfilled at all life-cycle stages in all scenarios)*

Life-cycle stage	**Default Scenario**		**Alternative Scenario (A-Composting, B-Anaerobic Digestion)**	
	Frozen Broccoli	**Fresh Broccoli**	**Frozen Broccoli**	**Fresh Broccoli**
Agricultural Production	Similar for both frozen and fresh broccoli in all three scenarios. 100% produced locally in Ontario.			
Processing and packaging	Includes washing, cutting, freezing and packaging. ***FW: 75% landfilled, 25% composted***	Includes washing, cooling and packaging in bulk. ***FW: 75% landfilled, 25% composted***	Includes washing, cutting, freezing and packaging. ***All FW sent to composting (Scenario A) or anaerobic digestion (Scenario B)***	Includes washing, cooling and packaging in bulk. ***All FW sent to composting (Scenario A) or anaerobic digestion (Scenario B)***
Distribution and Retail	Includes frozen transportation and frozen storage. No additional packaging used in grocery shopping. ***All FW and packaging waste landfilled.***	Includes cold transportation and storage. One plastic bag used during grocery shopping. ***FW: 75% landfilled, 25% composted***	Includes frozen transportation and frozen storage. No additional packaging used in grocery shopping. ***All FW and packaging waste landfilled.***	Includes cold transportation and storage. One plastic bag used during grocery shopping. ***All FW sent to composting (Scenario A) or anaerobic digestion (Scenario B)***
Household consumption	Includes energy and water usage for in-home storage and cooking. ***FW:50% landfilled, 50% composted***	Includes energy and water usage for in-home storage and cooking. ***FW: 75% landfilled, 25% composted***	Includes energy and water usage for in-home storage and cooking. ***All FW sent to composting (Scenario A) or anaerobic digestion (Scenario B)***	Includes energy and water usage for in-home storage and cooking. ***All FW sent to composting (Scenario A) or anaerobic digestion (Scenario B)***

4.1.1.5 Sensitivity Analysis

The current LCA studied the environmental impacts of fresh and frozen broccoli produced 100% locally in Ontario. However, when actual market trends are considered, approximately 82% of the broccoli and cauliflower consumed in Canada are imported, primarily from the United States (Agriculture and Agri-Food Canada, 2018). Thus, a sensitivity analysis was carried out assuming 82% of the broccoli that reaches the Regional Distribution Centers are imported from the United States, with the remaining 18% being produced locally.

4.1.1.6 System boundaries

The cradle of resources for the current LCA is the farm where broccoli is grown and the grave would be the waste treatment stage, where fresh/frozen broccoli lost and wasted along the supply chain would be discarded/treated. The impacts of wasted broccoli are also incorporated into the calculation at each stage of the life cycle. The LCA is conducted for the context of fresh and frozen broccoli produced and consumed in Ontario. Thus, the geographical context is the province of Ontario in Canada. The time horizon for the study is from 2008 to 2020 based on the data availability.

The current LCA only considers the broccoli consumed in households, and it excludes the context of restaurants and other food service stages. The amounts of purchasing, size of packaging, the method of preparation and quantities of food loss and waste would be different at food services than households. Thus, this study is not applicable for broccoli consumed in restaurants. Moreover, since broccoli provides nutrition to human body, in an ideal scenario, LCA should also include the treatment of sewage after digestion and excretion to assess environmental impacts due to emissions from wastewater. However, to calculate the impacts of sewage, the exact biochemical reactions inside the human body should be assessed and quantified with reference to 1 kg of broccoli consumed. This LCA only accounts for the associated food loss and waste up to the consumption stage, also including the plate waste of leftover food. In addition to considering food loss and waste at each life cycle stage in a mass balance approach, waste disposal and treatment is also included in the LCA. A mass balance approach is used to calculate the production quantities after allowing for the waste at each stage.

4.1.1.7 Assumptions and limitations

- The primary assumption of this study is that the agricultural production system in Ontario where broccoli is grown and harvested is similar to that of integrated production standard in Europe. This assumption is made based on the fact that both locations are situated in a temperate region with approximately similar weather conditions throughout the year.
- In Ontario, mostly the vegetable processing is done at the facilities on the farms (Veeramani, 2015), thus, it is assumed that the transportation distance from farm to processing facility (T1 in Figure 12) is zero or non-significant.
- It is assumed that input and output flows during vegetable processing in Ontario food processing facilities are similar to that of food processing facility in UK, which was studied by Canals et al. (2008).
- Given the limited availability of recent data in Canada regarding processing and packaging of broccoli, LCA inventory from UK was adopted to the study context. Based on the assumption that the technology in freezing fresh vegetables did not change significantly

over the last 15 years, the energy consumption values of vegetable freezing facilities obtained between 2005 to 2008 are used in the present study (Canals et al., 2008).

- It is assumed that 75% of FW during processing stage in both frozen/fresh systems, and fresh broccoli waste at retail are landfilled and the remaining 25% is composted. However, wasted broccoli at distribution and retail stages in the frozen product system are assumed to be landfilled, since it is unrealistic that the distributors/retailers would remove individual packaging for those to be sent for composting (see Table 11).
- At households, 50% of FW is assumed to be composted and the remaining 50% landfilled in the default scenario based on the estimates from Food and Organic Waste Framework of Ontario (Government of Ontario, 2018).
- Frozen broccoli is packaged in plastic packaging and stored in larger cardboard boxes for transportation to retailer. However, as fresh broccoli is sold loose, they are usually transported in large plastic crates which are reused many times. Assuming that the impact associated with plastic crates per one kg of consumed broccoli is negligible, the plastic crates are not included into the LCA of fresh broccoli.
- Although frozen broccoli is sold in individual packaging of smaller quantities, fresh broccoli is usually sold lose, as florets. It is assumed that Canadian consumers use a single plastic bag to hold 1-2 kg of broccoli purchased. Although consumers may use another large bag (reusable or single use) to carry all grocery items together, the second bag is considered to be out of the system boundary for the current study. Nevertheless, considering the usage of the larger second bag would be similar in both fresh and frozen broccoli systems, it would not impact the product and reference system comparison.
- Food preparation data from UK households is used for the context of Ontario, assuming that home cooking appliances and broccoli preparation methods in Ontario households are

similar to that of UK households. Therefore, it is assumed that electric stoves are used for the home cooking

- Canadian consumers generally buy a week's or several weeks' worth of groceries at once and transport all the groceries to households as bulk. Transportation mode could be a passenger vehicle, public transportation or walking. However, given that the impact from transportation would be more or less similar across all scenarios studied in the current LCA, and based on evidence from Veeramani (2015), the impacts due to transportation during grocery shopping for 1 kg of consumed broccoli were assumed to be negligible.
- Two alternative scenarios were studied assuming composting/anaerobic digestion as the primary waste treatment method given that most municipalities in Ontario now encourage source separation of organic waste for resource recovery. According to the Food and Organic Waste Framework for Ontario, the Province is working on implementing a 'food and organic waste disposal ban' to prevent FW ending up in disposal sites (Government of Ontario, 2018). These alternative scenarios were previously described in section 1.1.3. All packaging waste was assumed to be landfilled.
- In the sensitivity analysis, it was assumed that 82% of frozen/fresh broccoli was grown in farms in US and were processed and packaged in the USA. The average transportation distance from the processing facility in US to the regional distribution centers in Ontario was assumed to be 3000 km based on food-miles data from Kissinger (2012). The remaining 18% of frozen/fresh broccoli were assumed to be produced, processed and packaged in Ontario. For the proportion of broccoli imported from the USA, FW at processing stage was assumed to be landfilled since more than 90% of all organic waste in the USA is still landfilled. All other waste treatment steps remained the same as the default waste scenario.

4.1.1.8 Impact categories

The potential environmental impacts associated with production and consumption of food spans across a broad range from climate change to acidification, eutrophication, resource depletion and biodiversity loss. Considering the current political context of Ontario (Veeramani, 2015), and the nature of data availability, the present LCA focuses primarily on the Climate Change due to GHG emissions as the main impact category. GHG emissions are standardized to CO_2 equivalents and are measured using the TRACI 2.1 impacts assessment method as the Global Warming Potential (GWP) over a hundred-year time period, as it is the recommended IPCC method considered in TRACI (Veeramani, 2015). Other than that, Acidification Potential (AP), and Eutrophication Potential (EP), Ozone Depletion Potential (ODP), and Resource Depletion Potential (RDP) will also be quantified. LCIA was carried out using OpenLCA software with majority of the data for processes were based on ecoinvent 3.3 database (ecoinvent, 2016).

4.1.2 Life cycle inventory analysis

The process flowchart for frozen and fresh broccoli product systems modeled in the present study is illustrated in Figure 12 below. Inputs and outputs for individual processes are denoted with arrows and transportation is denoted as T_n between each stage. Inputs and outputs for the process of agricultural production remain same in both frozen and fresh broccoli supply chains which is expanded in Figure 13. Instances where fresh broccoli supply chain is different from frozen broccoli supply chain, component that belongs to the fresh broccoli supply system is denoted in green colour.

4.1.3 Process flowchart

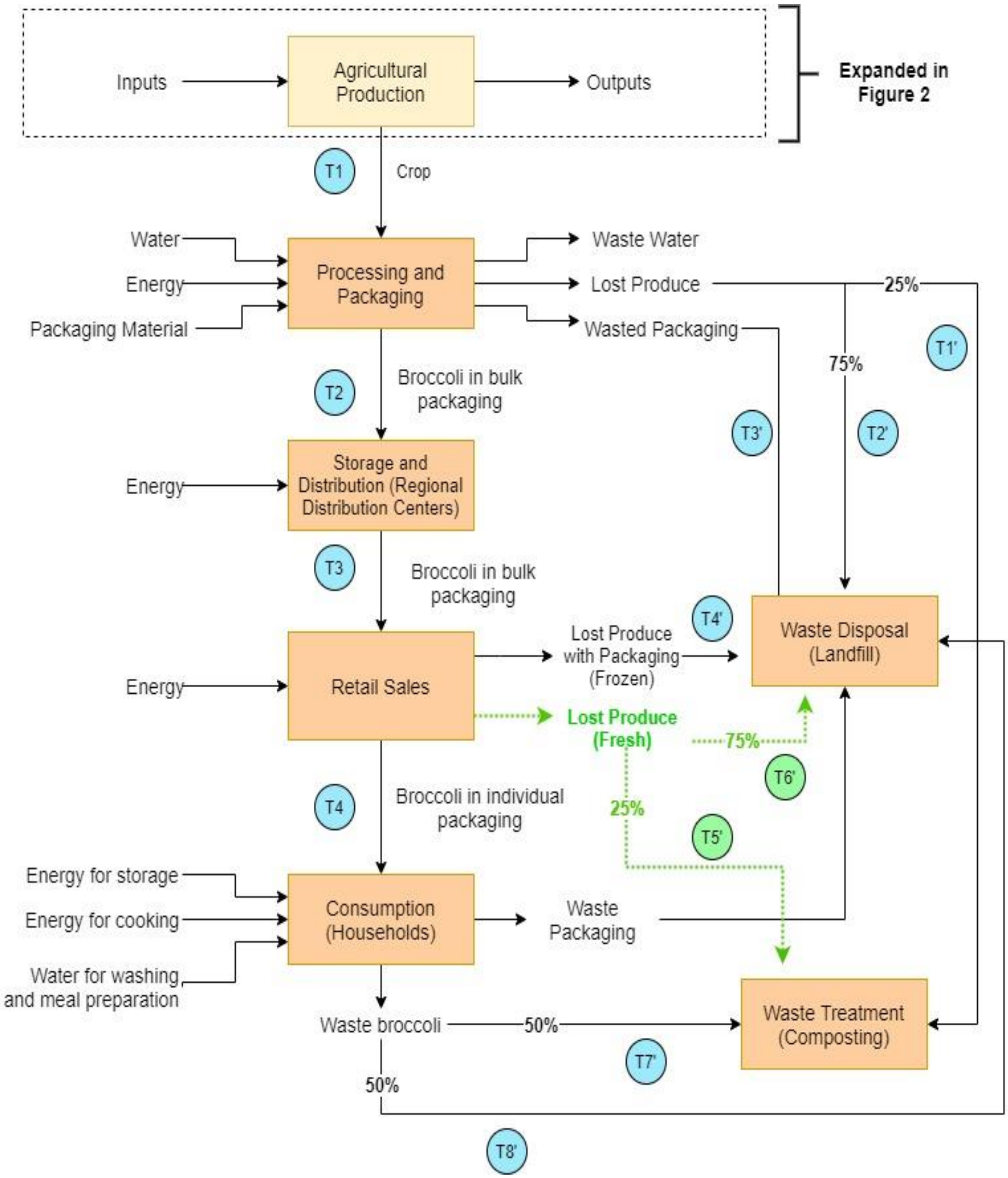

Figure 12: Process flow diagram of the product system – frozen broccoli. T1 to T4 represents transportation of broccoli from one stage to another, and T1' to T8' represents transportation of solid waste to landfills/composting at each stage. Flows demarcated in green colour are specific to fresh broccoli supply chain.

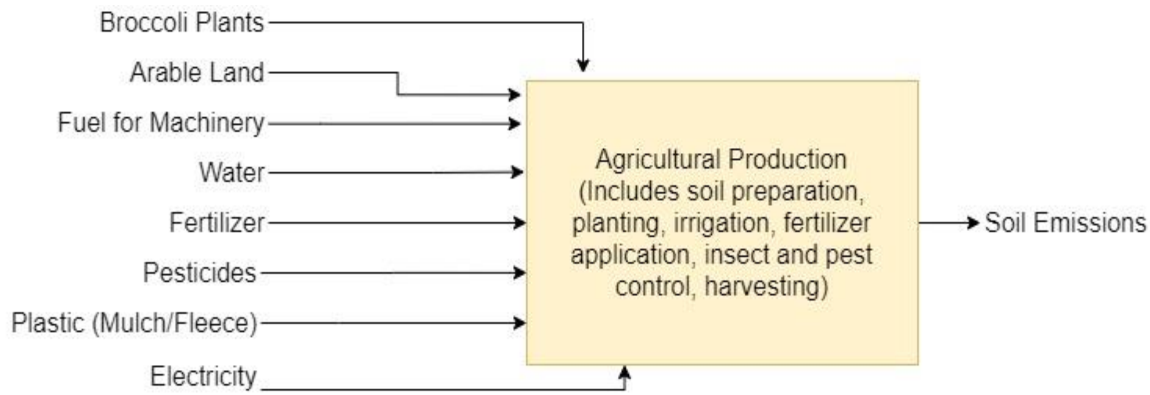

Figure 13: Expanded input flows for agricultural production stage

4.1.4 Data collection

Primary data for agricultural production of broccoli is obtained from the ecoinvent database and modified to suit the production conditions in Canada by changing the electricity grid mix (ecoinvent, 2016; Veeramani, 2015). For processing and packaging of both fresh and frozen broccoli, data was obtained from a study done in the UK by Canals et al. (2008), assuming that the processing technology and the facilities are similar in UK and Ontario. However, the conditions are adjusted to suit the Ontario grid mix. Estimates of transportation distances are based on the food distribution data for Ontario (Kissinger, 2012; Veeramani, 2015). Food loss and waste percentages were estimated based on the findings from Canals et al. (2008) and Gooch & Nikkel (2019). Input and output flows for each unit process modeled in the LCA is summarized in Table 12 below.

Table 12: Input and output flows from cradle to grave of fresh and frozen broccoli considered in the study

Flow type	Flow	Unit	Amount		Data Source
			Frozen Broccoli	Fresh Broccoli	
Agricultural production					
Input	All inputs illustrated in figure 13				Available in ecoinvent data base
Output	Broccoli (harvested)	kg	1	1	
Processing and packaging					
Input	Harvested Broccoli	kg	1.177	1.14	Calculated based on mass-balance
Input	Electricity	KWh	0.1326	0.0363	Averaged value from the data collected at four farms in UK (Canals, Munoz, Hospido, Plassmann, & McLaren, 2008)
Input	Natural gas	KWh	0.0327	n/a	
Input	Water	m^3	0.0109	n/a	
Input	Plastic for packaging (LDPE)	kg	0.002		
Input	Cardboard boxes	kg	0.0228		
Output	Food loss at processing facility	kg	0.177	0.14	Estimated based on Canals et al. (2008)
Transportation	Distance to waste treatment facility	km	15	15	Estimated based on (Government of Ontario, 2018)
Output	Packaged broccoli	kg	1	1	
Storage at Regional Distribution Centers					
Input	Input of packed broccoli	kg	1	1	
Transportation	Transportation distance to RDC	km	38	38	Based on Ontario food distribution data (Veeramani, 2015)
Input	Electricity	MJ	0.1	0.019	(Canals et al., 2008)
Output	Packaged broccoli	kg	1	1	

Flow type	Flow	Unit	Amount		Data Source
			Frozen Broccoli	**Fresh Broccoli**	
Retail					
Input	Input of Packaged broccoli	kg	1.017	1.0196	Calculated based on mass-balance
Transportation	Transportation distance to retailer	km	500	500	Based on Ontario food distribution data (Veeramani, 2015)
Input	Electricity	MJ	4	0.21	(Canals et al., 2008)
Input	Packaging (LDPE)	kg	0.005	0.01	Weighing of plastic bag
Output	Food loss at retailer	kg	0.0095	0.0196	Estimated based on Canals et al. (2008) and Martindale (2014)
Output	Waste packaging	kg	0.0075		(Canals et al., 2008)
Transportation	Distance to composting facility	km	15	15	Estimated based on (Government of Ontario, 2018)
Transportation	Distance to landfill	km	15	15	
Output	Broccoli purchased	kg	1	1	
Household Consumption					
Input	Broccoli purchased	kg	1.059	1.25	Calculated based on mass-balance
Input	Electricity home storage	MJ	0.59	0.16	UK consumers (Canals et al., 2008)
Input	Electricity cooking	MJ	3.9	3.9	
Input	Natural Gas cooking	MJ	6.3	6.3	
Input	Tap water	L	8.6	10.2	
Output	Wasted broccoli	Kg	0.052	0.25	Estimated based on Canals et al. (2008) and Gooch and Nikkel (2019)
Output	Waste Packaging LDPE	Kg	0.007	0.005	Frozen - Canals et al. (2008), Fresh – From LCA Database (for 1 plastic bag)

Flow type	Flow	Unit	Amount		Data Source
			Frozen Broccoli	Fresh Broccoli	
Transportation	Distance to composting facility	km	15	15	Estimated based on (Government of Ontario, 2018)
Transportation	Distance to landfill	km	15	15	

4.2 Results

4.2.1 LCIA of frozen and fresh broccoli produced and consumed in Ontario

For frozen and fresh broccoli produced and consumed in Ontario, frozen broccoli showed higher impacts compared to fresh broccoli, for all categories except for EP (Table 13). As depicted in Figure 14, relative impacts are higher in frozen broccoli by more than 20% in two impact categories, ODP and RDP (fossil fuels), and by more than 10% in AP and GWP.

Table 13: LCIA results of selected impact categories for fresh and frozen broccoli

Impact category	Unit	Fresh broccoli	Frozen broccoli
Acidification	kg SO_2 eq.	6.11×10^{-3}	7.01×10^{-3}
Eutrophication	kg N eq.	9.03×10^{-3}	8.35×10^{-3}
Global Warming	kg CO_2 eq.	1.54	1.72
Ozone Depletion	kg CFC^{-11} eq.	1.66×10^{-7}	2.19×10^{-7}
Resource depletion - fossil fuels	MJ surplus	1.91	2.40

Process contributions for the selected impact categories in fresh and frozen broccoli product systems are illustrated in Figure 15. Process contributions were calculated in relation to the five main processes in the life-cycle of the product and reference systems, i.e., agricultural production, processing and packaging, regional storage, retail and consumption at households. Consumption at households was observed to be the largest contributor to GWP, ODP and RDP, while agricultural production contributed mostly to AP and EP.

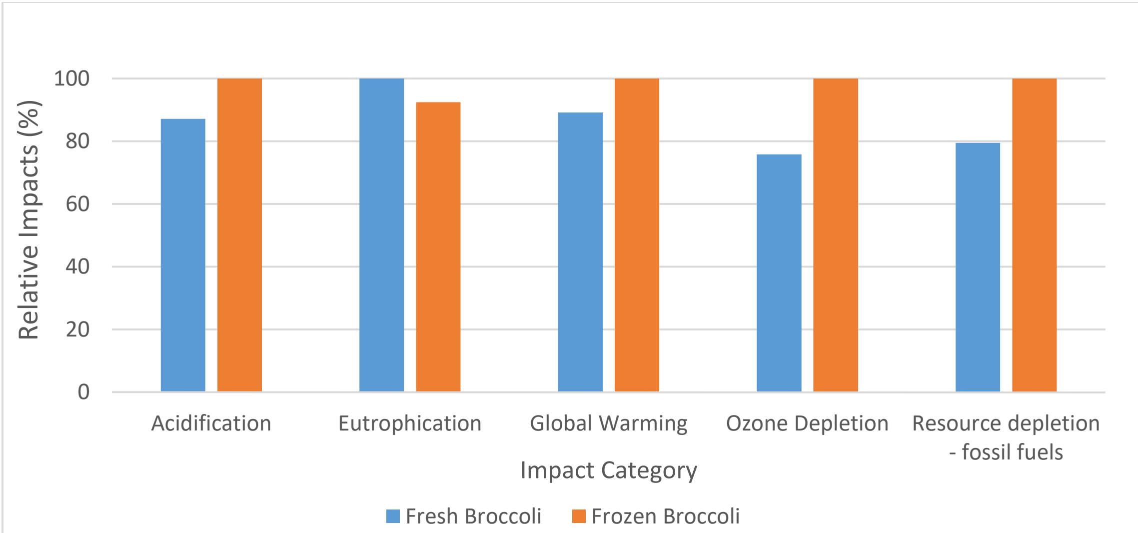

Figure 14: Relative indicator results for fresh and frozen broccoli. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result.

It was observed that frozen broccoli had higher environmental impacts than the fresh broccoli, especially at the retail stage considering all impact categories. This could be mainly due to higher energy requirement for freezing than cooling. In addition, differences in waste treatment methods at retail stage for fresh and frozen broccoli could also have resulted higher impacts in frozen broccoli, since it was assumed that all FW at retail stage would be landfilled in frozen broccoli system.

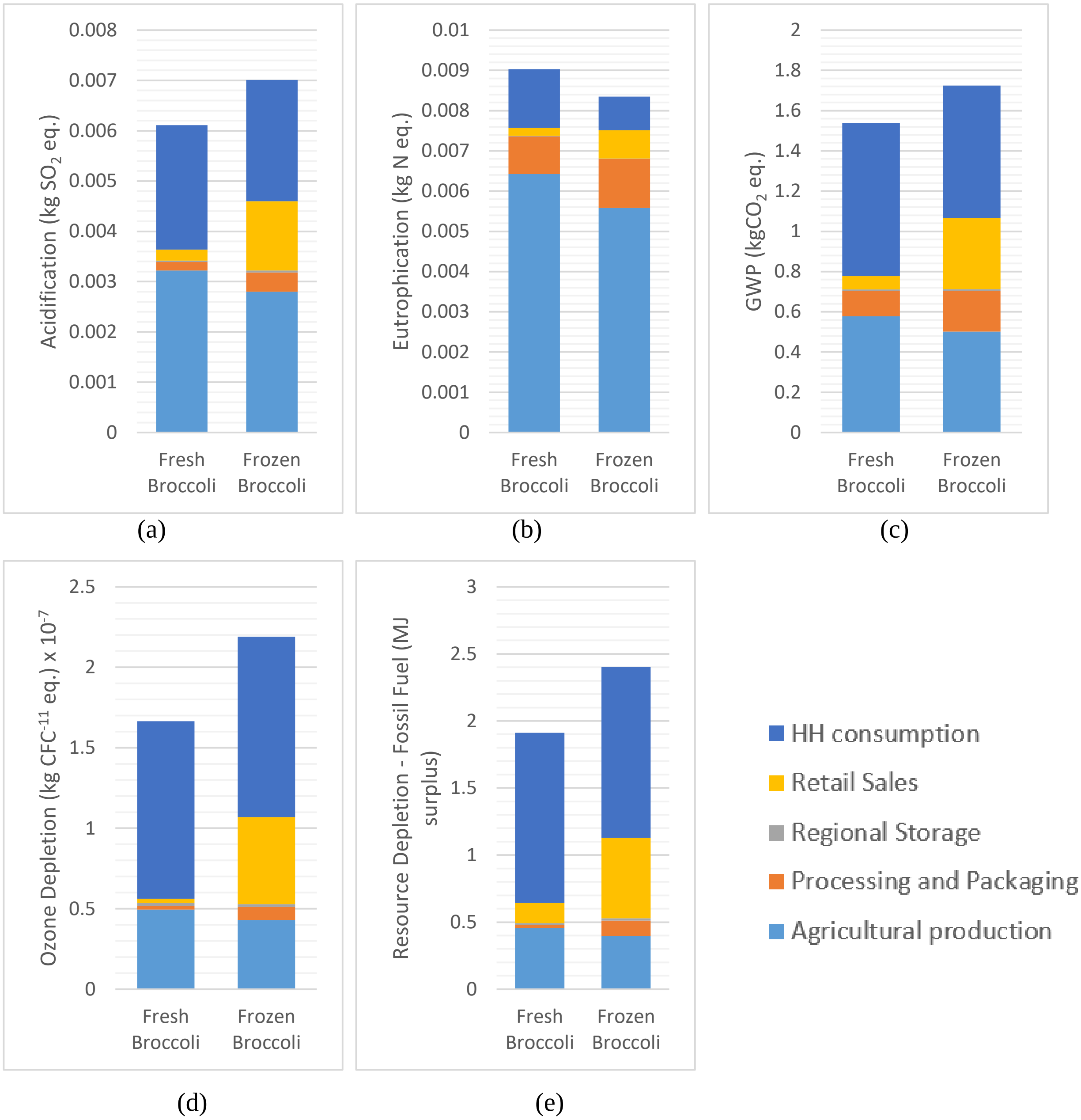

Figure 15: Process contribution for fresh and frozen broccoli for (a) acidification, (b) eutrophication, (c) global warming potential, (d) ozone depletion potential, and (e) resource depletion potential at agricultural production, processing and packaging, regional storage, retail and household (HH) consumption.

According to the LCIA results of the current study, AP is higher in frozen broccoli than in fresh broccoli. Nevertheless, a few interesting trends were revealed when observing the process contributions (Figure 15). In contrast to the total AP, process contributions for AP were slightly higher in the fresh than in the frozen broccoli product system in the agricultural production and household consumption stages. However, contribution to AP at processing, regional storage and retail processes were notably higher in frozen broccoli, resulting in overall higher AP compared to fresh broccoli. It is notable that this trend is observed in all five impact categories (Figure 15 (a) to (e)).

The reason for the generation of higher AP in fresh broccoli at agricultural production stage is due to the higher the reference flow of harvested broccoli. When mass balance is considered accounting for all FW along the life cycle, 1.41 kg of fresh broccoli should be produced in order to consume 1 kg at the households whereas for the consumption of 1 kg of frozen broccoli, production should only be 1.24 kg. Similarly, at the household, the amount of FW generated when consuming fresh broccoli was higher than frozen broccoli due to mass balance, resulting in comparatively higher impacts associated with waste treatment.

In contrast, energy requirements for freezing during storage and transportation might have led to higher AP for frozen broccoli, especially during retail and regional distribution processes. At the processing and packaging stage it is evident that frozen broccoli shows higher AP than fresh broccoli due to additional steps of processing, packaging and freezing as opposed to mere washing and bulk packaging of fresh broccoli.

Agricultural production dominated the EP impact category in both fresh (6.42×10^{-3} kg N eq.) and frozen (5.58×10^{-3} kg N eq.) broccoli systems accounting for 71.1% and 66.8% of total EP respectively. This is due to the nitrogen and phosphorous emissions to the hydrosphere that takes place predominantly in the agricultural production stage. The second highest contribution was from household consumption for both fresh (1.46×10^{-3} kg N eq.) and frozen broccoli (8.4×10^{-4} kg N eq.), mainly due to electricity usage for storage and natural gas usage for cooking. In addition, landfilling wasted frozen broccoli with packaging at retail had a EP of 1.9×10^{-4} kg N eq., which resulted in the comparatively higher contribution from retail sales. However, it is evident that overall higher EP in fresh broccoli compared to frozen broccoli resulted from significantly higher impacts from agricultural production. As explained earlier in relation to AP, requirement to produce larger quantity of fresh broccoli due to associated FW along the supply chain might is the reason for the observed higher EP at agricultural production.

The highest contribution to GWP in both fresh and frozen broccoli was from household consumption followed by agricultural production. Similar to the trend observed with acidification, GWP was comparatively higher in fresh broccoli than in frozen broccoli at agricultural production and consumption at households' stage. However, due to higher impacts at processing and retail stages, overall GWP of frozen broccoli was higher than that of fresh broccoli. This indicated that although the impacts from FW are higher in fresh broccoli system, those are outweighed by the impacts due to processing, packaging and storage needs of frozen broccoli, resulting in an overall higher GWP.

ODP is mostly dominated by consumption at households' stage for both fresh (1.10×10^{-7} kg CFC^{-11} eq.) and frozen broccoli (1.12×10^{-7} kg CFC^{-11} eq.). This is mainly due to the usage of natural gas for cooking at households. The second highest contribution for ODP in fresh broccoli is from agricultural production (4.95×10^{-8} kg CFC^{-11} eq.), whereas in frozen broccoli, contribution from retail sales (5.39×10^{-8} kg CFC^{-11} eq.) exceeds that from agricultural production (4.30×10^{-8} kg CFC^{-11} eq.). These results suggest that refrigerant use for frozen storage and frozen transportation from regional distribution centers are major hotspots for ODP at retail sales for frozen broccoli.

In the current LCIA, RDP for fresh and frozen broccoli showed similar trends to ODP, with household consumption being the highest contributor. For frozen broccoli, the contribution from retail sales was the second highest as opposed to agricultural production in fresh broccoli. Similar to the results observed with ODP, retail sales impacts for frozen broccoli were dominated by frozen storage and frozen transportation. Interestingly, for fresh broccoli, RDP at retail sales was mostly impacted by the packaging use, which has resulted from the use of single-use polythene bag to hold broccoli florets during shopping.

Overall, these results indicate that even though frozen broccoli generates less FW along the life cycle, its environmental impacts are comparatively higher than fresh broccoli, except for impacts due to Eutrophication. Impacts associated with waste treatment throughout the life cycle were observed to be higher in fresh broccoli for all impact categories except for EP. It should be emphasized that the current study used a conservative approach by assuming all FW generated at retail stores is landfilled along with the packaging as mixed waste. Although this might have overestimated the impacts of landfilling, cumulative impacts due to waste treatment of frozen broccoli are less than that of fresh broccoli in four impact categories. Together, these results suggest that frozen broccoli has higher environmental impacts than fresh broccoli, especially due to required frozen storage and transportation.

4.2.2 Scenario Analysis - Alternative waste treatment methods

Two scenarios where the primary waste treatment method is changed to composting or anaerobic digestion instead of landfilling were assessed to understand how the impacts change if more waste recovery was practiced instead of disposal. In each of these scenarios, it is assumed that all FW generated in the fresh broccoli system (reference system) is sent to composting (Scenario A) or anaerobic digestion (Scenario B) and the packaging waste is landfilled. In the frozen broccoli system (product system), it is assumed that FW generated at the retailer is landfilled along with polythene packaging, and all other FW generated along the life cycle is treated either by composting (Scenario A) or anaerobic digestion (Scenario B).

Table 14: LCIA results of Fresh and Frozen broccoli with the two waste treatment scenarios, composting (Scenario A) and anaerobic digestion (Scenario B).

Impact Category	Reference Unit	Fresh Broccoli		Frozen Broccoli	
		Composting	Anaerobic digestion	Composting	Anaerobic digestion
Acidification	kg SO_2 eq.	6.62×10^{-3}	6.20×10^{-3}	7.29×10^{-3}	7.13×10^{-3}
Eutrophication	kg N eq.	7.17×10^{-3}	7.34×10^{-3}	7.36×10^{-3}	7.44×10^{-3}
Global Warming	kg CO_2 eq.	1.47	1.42	1.70	1.67
Ozone Depletion	kg CFC^{-11} eq.	1.66×10^{-7}	1.66×10^{-7}	2.19×10^{-7}	2.19×10^{-7}
Resource depletion - fossil fuels	MJ surplus	1.89	1.92	2.40	2.41

The results suggest that even when the FW treatment option is changed to anaerobic digestion, frozen broccoli showed comparatively higher impacts than fresh broccoli in all impact categories. Process contributions (Figure 16) were considerably similar to the trends observed with composting as the FW treatment scenario.

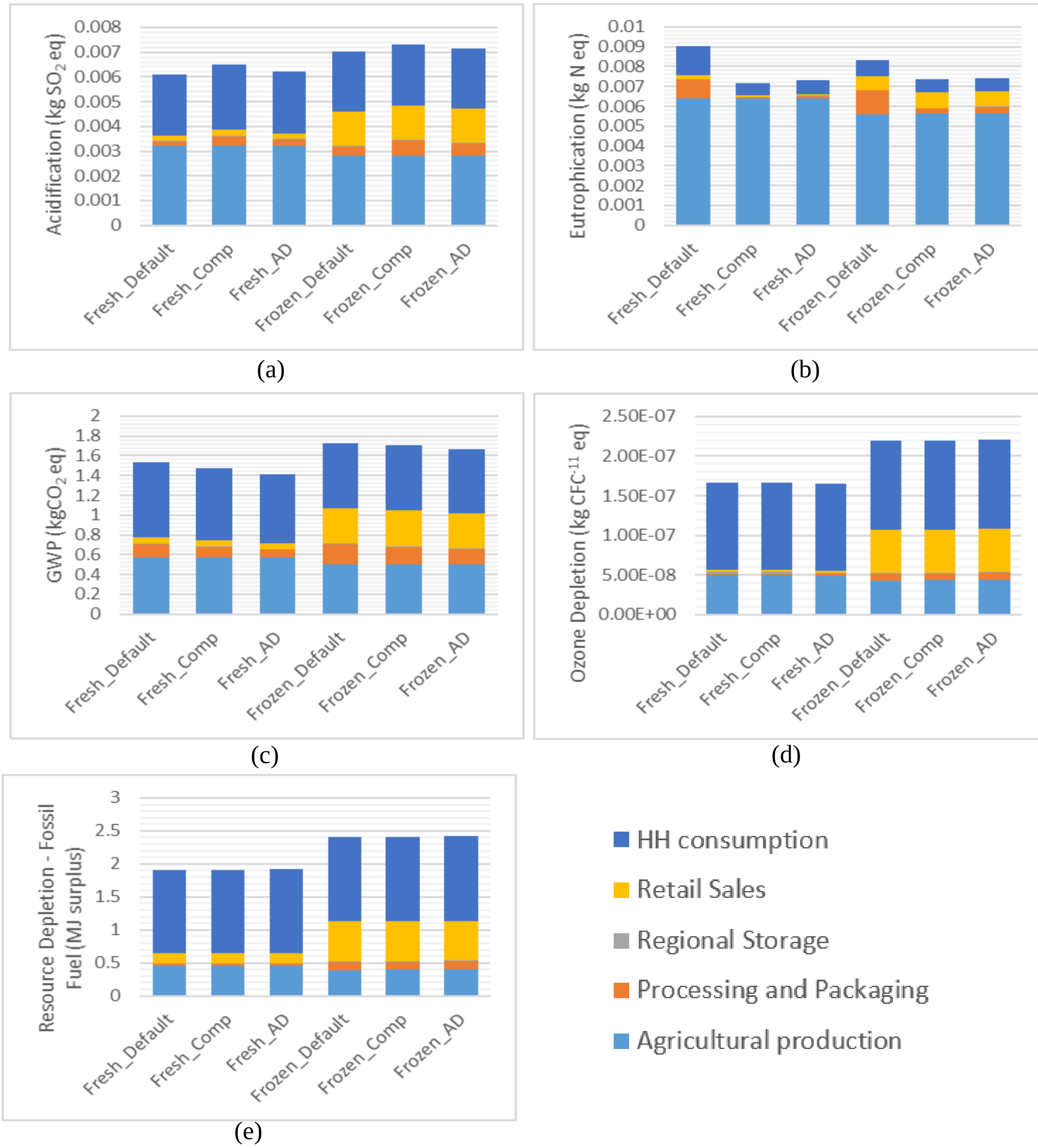

Figure 16: Process contributions in frozen and fresh broccoli in three waste treatment scenarios for (a) acidification, (b) eutrophication, (c) global warming potential, (d) ozone depletion potential, and (e) resource depletion potential (Comp=Scenario A, AD=Scenario B).

When the three waste treatment scenarios were compared for both fresh and frozen broccoli, it was observed that the default scenario, which reflects the current waste treatment practices in Ontario, has relatively higher impacts in all impact categories except for AP. When the majority of FW is treated using either composting or anaerobic digestion instead of disposal into a landfill, it notably reduces impacts related to EP, GWP and RDP, although the reduction of ODP is negligible. However, AP was observed to be higher in both composting and anaerobic digestion when compared to the default waste treatment scenario. These findings suggest that overall environmental impacts from both fresh and frozen broccoli supply chains can be reduced by opting into organic waste recovery methods instead of disposal in landfills.

Composting generated comparatively higher impacts than anaerobic digestion in relation to AP and GWP, whereas anaerobic digestion generated higher EP and RDP than composting. Moreover, ODP of fresh broccoli was higher in composting, but for frozen broccoli, anaerobic digestion resulted in slightly higher contribution to ODP. This suggests that within the scope of the current study, it is not possible to declare that overall environmental impacts from either composting or anaerobic digestion is higher or lower than the other.

4.2.3 Sensitivity analysis

4.2.3.1 Accounting for the market share for imports from US

According to Statistics Canada (CATSNET, 2018), approximately 82% of the broccoli and cauliflower consumed in Canada are imported. Considering United States as the primary supplier for these imports, a sensitivity analysis was carried out assuming 82% of the broccoli that reaches the Regional Distribution Centers are imported from US, with the 18% remaining being produced locally. The following section outlines the LCIA results for above scenario.

Table 15: Comparison of LCIA results for fresh and frozen broccoli assuming 100% local production with 82% imports

Impact Category	**Reference Unit**	**Fresh Broccoli**		**Frozen Broccoli**	
		100% local	**82% imported**	**100% local**	**82% imported**
Acidification	kg SO_2 eq.	6.11×10^{-3}	8.35×10^{-3}	7.01×10^{-3}	9.10×10^{-3}
Eutrophication	kg N eq.	9.03×10^{-3}	9.95×10^{-3}	8.35×10^{-3}	9.70×10^{-3}
Global Warming	kg CO_2 eq.	1.54	1.96	1.72	2.14
Ozone Depletion	kg CFC^{-11} eq.	1.66×10^{-7}	2.69×10^{-7}	2.19×10^{-7}	3.13×10^{-7}
Resource depletion - fossil fuels	MJ surplus	1.91	2.73	2.40	3.12

Sensitivity analysis shows that the environmental impacts of both fresh and frozen broccoli increase drastically when the import scenario is taken into consideration. In the current LCA, the transportation from processing facility to regional distribution centers is incorporated into regional storage process, which has contributed to the drastic increase in impacts in the import scenario. Ground transportation of fresh and frozen broccoli from US to Canada has contributed to 24.56% and 19.02% of AP, 20.5% and 15.5% of GWP, 39.92% and 26.69% of ODP, and 29.63% and 21.76% of RDP, respectively. Impacts during agricultural production and processing stages increased slightly in all impact categories due to the differences in the energy grid in US and Canada whereas the most notable increase was observed in regional storage stage due to transportation.

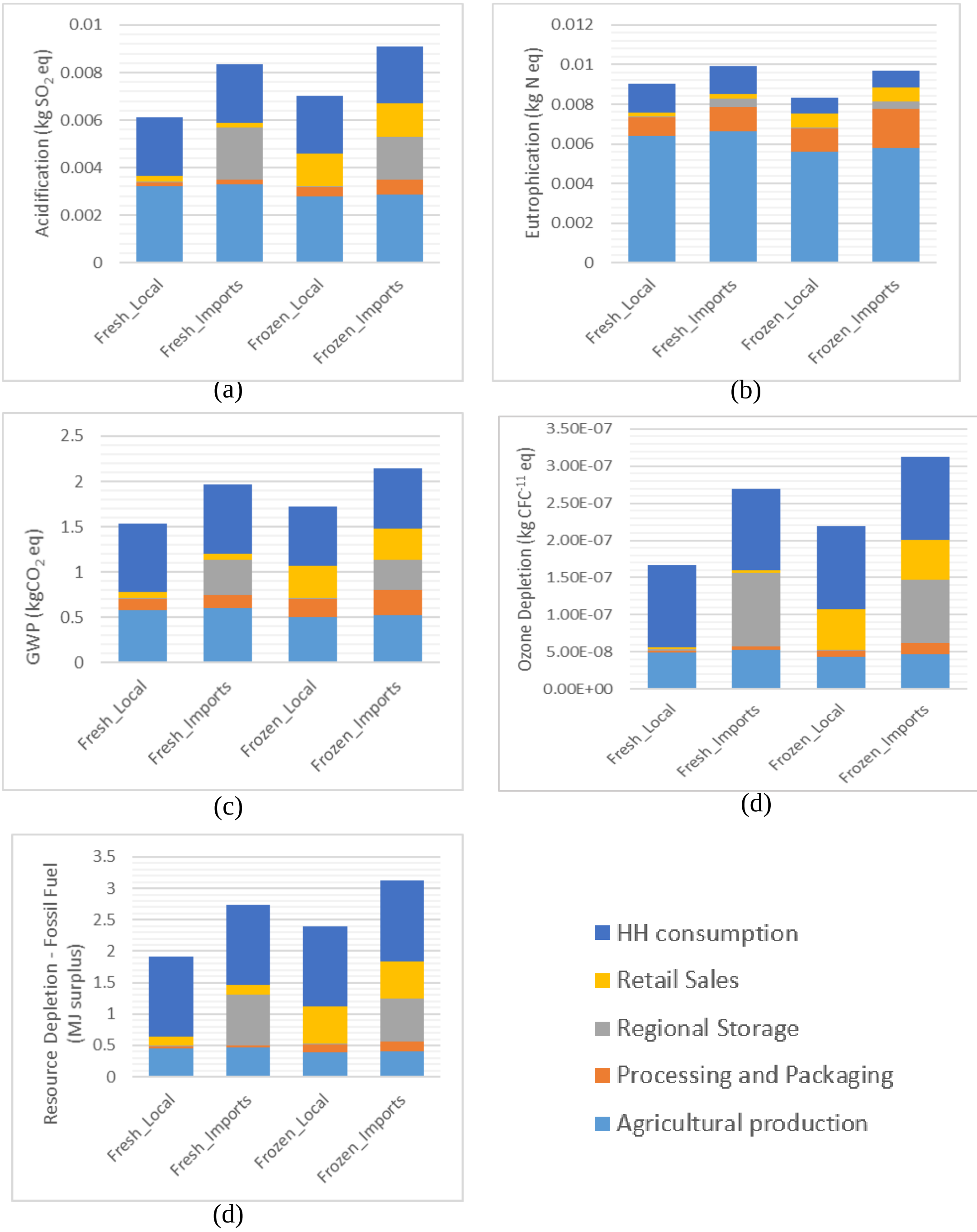

Figure 17: Process contribution in frozen and fresh broccoli for 100% local production and 82% imports for (a) acidification, (b) eutrophication, (c) global warming, (d) ozone depletion, and (e) resource depletion (Local=100% local production, Imports=82% imported from US)

4.2.3.2 Assessing if freezing impacts can be outweighed by further reducing FW

Findings of the present LCIA suggest that freezing impacts associated with the frozen broccoli supply chain is much higher than the excess FW impacts associated with fresh broccoli, making frozen broccoli more environmentally unsustainable than fresh broccoli. It is important to assess if it is possible to offset the impacts due to freezing by further reducing FW along the supply chain. With the increased shelf life of frozen broccoli, it is possible to avoid FW at retail stores through careful planning. Thus, a sensitivity analysis was carried out assuming that all frozen broccoli that reaches the retail gets sold generating zero FW at retail for the frozen broccoli supply chain. This analysis found out that even with no FW at retail, impacts from frozen broccoli are still higher than from fresh broccoli in all impact categories (AP: 7.19 x 10^{-3} kg SO_2 eq., GWP: 1.66 kg CO_2 eq., ODP: 2.18 x 10^{-7} kg CFC^{-11} eq., and RDP: 3.39 MJ surplus) except for EP (7.01 x 10^{-3} kg N eq.).

4.3 Discussion

The present study compared the life-cycle environmental impacts of fresh and frozen broccoli produced and consumed in Ontario to understand the contribution of FW to environmental impacts throughout the supply chain. Previous studies have suggested that frozen vegetables could be a potential alternative to reduce the impacts of FW associated with fresh vegetables (Janssen et al., 2017; Martindale & Schiebel, 2017). Thus, the present study was designed to determine if the reduced impacts due to lesser FW was sufficient to offset the impacts due to additional processing in frozen broccoli supply chain. Moreover, the present LCA also seeks to understand how different waste treatment scenarios can change the overall life-cycle environmental impacts in frozen and fresh produce supply chains.

Findings of the current study suggest that frozen broccoli has up to X % higher environmental impacts related to acidification, global warming, ozone depletion and resource depletion. Frozen broccoli performs better only in relation to eutrophication due to the lower FL and FW, which requires less harvested broccoli, and therefore less eutrophication impacts related to agricultural production. This finding seems to be consistent with the previous study in the UK by Canals et al. (2008), which also reported that frozen broccoli has comparatively higher environmental impacts in relation to a number of impact categories including AP and GWP, while fresh broccoli shows higher EP. In another study that compared fresh imported and frozen domestic blueberries in US found that fresh blueberries perform better in a range of impact categories, even when imported, than domestic frozen blueberries (Chapa et al., 2019). Hence, it could be suggested that fresh broccoli has comparatively lower impacts in the selected impact categories than frozen broccoli in the context of the present study.

In both fresh and frozen broccoli, the hotspots were agricultural production and household consumption in all impact categories, which was also observed in the study by Canals et al. (2008). However, the significant difference between the two product systems was observed in processing and retail processes indicating that the impacts due to freezing, frozen transportation and frozen storage are what resulted in higher impacts for frozen broccoli. This evidence suggests that although the cumulative impacts due to FW could be higher in fresh broccoli, the impacts due to processing and frozen storage outweigh them. Within the context of the current study, it is not plausible to recommend frozen broccoli as an effective alternative for fresh broccoli considering only the reduced impacts due to FW.

The current study attempted to capture the existing waste treatment scenario in Ontario by assuming 50%-75% of organic waste is landfilled and the remaining is composted. A scenario analysis was carried out to understand how the environmental impacts change if a maximum amount of FW is recycled by means of composting or anaerobic digestion instead of disposing in a landfill. The findings from the scenario analysis suggest that overall impacts drop at least slightly for both composting and anaerobic digestion in all impact categories except for acidification. Several previous studies observed that composting and anaerobic digestion generally perform better than landfilling in many impact categories (Gao et al., 2017; Mondello et al., 2017)

Within the context of the present study, anaerobic digestion performed better than composting in certain impact categories and vice versa, making it difficult to state one method is better than the other. Similar mixed findings have been observed throughout literature (Mondello et al., 2017; Salemdeeb et al., 2018; Schott et al., 2016) indicating that the relative performance of each method highly depends on the system boundaries, variation of input data, assumptions related to bioconversion process, and the technology being used.

Findings from the sensitivity analysis where the market share of imported broccoli was varied from 0 to 82%, represent the average environmental impacts of one kg of broccoli typically consumed in Ontario. When the impacts due to transportation are considered, locally grown frozen broccoli appeared to have lesser impact in the selected impact categories within the context of the present study imported fresh broccoli.

Interestingly, even after reducing FW by 50% at processing and by 100% at retail, impacts associated with frozen broccoli were still higher than the impacts from fresh broccoli. This suggests that finding a trade-off between reduced FW and the additional impacts due to freezing in frozen broccoli seemed to be unrealistic. However, further research is needed to understand how the processing and frozen storage technologies can be made more sustainable to offset these impacts.

4.3.1 Limitations

It should be acknowledged that data quality could be a major limitation in this study, especially regarding the food processing in the Canadian context. Most of the input data for processing, storage, and retail were obtained from a single study done in the UK due to the unavailability of such data for the study context. Although it is assumed that production and market conditions are similar in Europe and Canada, this results in a significant uncertainty. Further research is needed using more recent Canadian data to clearly understand the impacts of fresh and frozen produce in Canadian supply chains.

Energy consumption for frozen storage in retail was estimated using shelf-life and market trend information for UK due to data limitations. It should be noted that impacts associated with frozen storage can drastically change with the storage duration at retail and the advancements in technology. Considering that frozen broccoli in the Canadian market usually has a shelf-life of over a year, it is possible that in reality, frozen broccoli can be stored in retail for a longer period of time, increasing overall impacts.

During the present study, transportation distances to all waste treatment facilities (landfill/compost/anaerobic digestion) were assumed to be similar. In reality, the distance to landfill could be different from the distance to a centralized composting facility, which may result in differences in overall impacts due to two waste management methods. Thus, for more accurate comparison between the waste treatment methods, future studies should use more rigorous data regarding the locations of waste treatment facilities.

4.4 Conclusion

This cradle-to-grave life cycle assessment compared the environmental profiles of fresh and frozen broccoli produced and consumed in Ontario and observed that fresh broccoli performs better in four out of five mid-point impact categories considered in this study. It also compared different waste treatment scenarios to understand how the overall impacts change with different FW management practices. Anaerobic digestion showed lowest impacts in three out of five impact categories, while composting showed better performance in the remaining two categories. Both anaerobic digestion and composting appear to be more sustainable than the existing real-life scenario where 50%-75% of FW is landfilled. Although frozen broccoli generates lesser impacts due to FW, cumulative impacts across the life-cycle are much higher than fresh broccoli. However, further research is needed to help retailers and food processors to make more informed decisions regarding environmental trade-offs between fresh and frozen produce, and to improve the cold supply chain by addressing hot-spots in processing and storage.

CHAPTER 5

Discussion and Conclusion

The FSC is rather unique compared to any other supply chain as it requires complex logistics specifically designed to address the handling of perishable material (Göbel et al., 2015). Perishability is one of the main reasons why integrating FW into a circular economy is more complicated than other waste sectors. Specific treatment systems are needed to recover energy and nutrients from wasted food as food transforms differently after its use, making it impossible to break down into components for recycling like other consumer goods (Bemmel & Parizeau, 2020). Therefore, reduction of FW at source of generation is more important than the treatment of FW after disposal. Understanding the quantities and composition of FW generation at each stage of the life-cycle, and exploring the potential of food preservation technologies to offset the impacts from FW are two extremely important aspects related to FW reduction. The present study attempted to contribute to the above two aspects by understanding the household FW composition in Region of Waterloo, Ontario, and comparing the life-cycle environmental impacts of fresh and frozen produce through a case study for broccoli.

The systematic literature review presented in the current study critically analyzed the strengths and limitations of four main FW quantification methods. The findings suggest that there is no 'one best' method for FW quantification at household level since the selection of the most appropriate method should depend on the research question each study is trying to answer and the level of access to resources. The simple decision tree presented in the study provides guidance to future researchers to select the most appropriate household FW quantification method depending on the research question.

If the study objective is quantification rather than composition analysis, the most accurate results can be obtained through a weight-based waste audit, given that the researcher has direct access and resources to collect and measure FW. Even if the research question is more biased towards composition than quantity, a composition based waste audit could still generate accurate estimates without the influence of subjectivity of participants. However, when the researcher does not have direct access or resources to collect FW, kitchen diary method can be utilized to capture quantity as well as composition data. Although the accuracy can be comparatively low in using 'Surveys' to quantify FW, they can be highly useful when the researcher also wants to understand the attitudes and beliefs related to food wasting behaviors. When the research objective is to understand the 'big picture' related to FW, it was observed that using secondary data to generate FW estimates would be the most effective.

The current literature review elaborated how it is extremely difficult to draw a valid comparison among quantities of FW in two countries or regions due to variabilities in study design even within a single method. Thus, it emphasized the importance of introducing internationally-accepted standard protocols for each method. The study also identified that lack of a standard classification for different types of FW is also a challenge in FW research and that it is important to develop a standard FW classification system.

Considering the findings from the literature review, a composition-based waste audit was carried out in the Region of Waterloo to understand how much of FW in households are avoidable, and what contributes mostly to this avoidable fraction. Findings of the waste audit suggested that 43% of FW from households in Waterloo is avoidable and that a majority of this avoidable FW is fresh fruits and vegetables that were purchased but discarded without even being prepared or served in a meal. Similar to the findings from a number of previous studies (Edjabou et al., 2016; Ventour, 2008; von Massow et al., 2019), the amount of animal-derived FW was observed to be comparatively low accounting for only 6% of the total FW. The findings further emphasize the importance of carrying out seasonal studies and following special holidays to capture a more holistic picture of household FW generation, such that appropriate interventions can be designed to reduce FW under these special circumstances.

The findings of the current pilot FW audit and several similar studies across Canada as well as in other countries emphasize how the perishability of fresh produce leads to enormous amounts of waste across the FSC. It was evident that it is very important to consider the life-cycle impacts of food preservation techniques such as freezing to understand whether they can offset the environmental impacts of FW. Considering broccoli as a case study vegetable, the final component of the research compared the life-cycle environmental impacts of fresh and frozen broccoli produced and consumed in Ontario.

Findings of the LCA suggest that frozen broccoli has comparatively higher environmental impacts related to acidification, global warming, ozone depletion and resource depletion, whereas eutrophication was higher in fresh broccoli due to the lower FL and FW. Agricultural production and household consumption were identified as hotspots in both fresh and frozen broccoli although the significant differences between the two systems were observed in processing and retail stages. It was also observed that the current waste treatment scenario in Ontario can be made more sustainable by increasing the fraction of FW sent for recycling through composting or anaerobic digestion rather than landfilling. Although the study basically focused on broccoli produced and consumed in Ontario, it was observed that in the realistic scenario, 82% of all broccoli consumed in Canada are imported, thus the actual environmental impacts of broccoli consumed in Ontario could be much higher due to transportation. Within the context of the present study, it was concluded that reduced FW in frozen broccoli is not sufficient to offset the environmental impacts of additional processing and frozen storage. The additional fossil energy use required for processing and storage increase the relative impacts, thereby offsetting the reduced impacts due to lower FW. This requires processing companies to look at more efficient technologies and cleaner energy.

The major contributions of the current research are trifold. Firstly, the literature review contributes to the research community by summarizing the strengths and limitations of FW quantification methods and by providing directions to future researchers in selecting the most appropriate method. Secondly, the pilot waste audit conducted in the Region of Waterloo contributes important information to the research community and policy makers by identifying the fraction and the composition of avoidable FW, and also emphasizing on the need for more rigorous studies in similar context. Finally, the LCA brings in valuable insights into research community, policy makers and consumers by elaborating how the life-cycle environmental impacts of frozen produce can still be much higher than that of fresh produce, although the amount of FW is comparatively low.

In conclusion, fresh fruits and vegetables are a crucial contributor to household FW generating enormous environmental impacts across the life-cycle. It is extremely important to conduct rigorous studies to understand how FW generation changes with the season and special instances such as holidays. Industries and policy makers should focus more on improving the energy efficiency in frozen supply chain, whereas consumers are encouraged to eat more locally grown fresh produce while paying careful attention to their meal planning, food storage and purchase patterns to avoid excessive generation of FW.

5.1 Limitations and directions for future research

Major limitations of the presented pilot household FW audit are the small sample size and inability to link collected waste samples to the source households. It is recommended that more rigorous studies should be carried out with a larger sample size and across different seasons and special holiday events. Collecting samples from the curbsides of selected neighborhoods rather than from the municipal waste collection facility will be beneficial to understand how external factors such as income and other demographic aspects can have an impact on food wasting behaviors.

Data quality was found to be one of the major limitations of the LCA component, especially regarding the food processing aspects in the Canadian context. It is recommended that future studies could use more context specific and recent data, possibly by collaborating with food processing industries in Ontario to further understand the environmental impacts of frozen produce. The present study considered only a single vegetable, broccoli, for the comparison, whereas future studies could benefit by focusing on other similar produce such as beans, carrots, peas, spinach, and other frozen vegetables and fruits.

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APPENDIX

Table A1: Composition of the 16 green bin waste samples analyzed in the current study

Sample no	Total weight	Wt-Food Waste	Unavoidable		Avoidable				Unidentifiable	Weight of Non-food materials
			Plant-based	Animal-derived	Prepared Plant-based	Prepared Animal-derived	Unprepared Plant-based	Unprepared Animal-derived		
1	2562.2	2403.1	420.1	0	267.1	0	659.5	580.2	476.2	159.1
2	1480.4	1090.3	101.0	0	176.7	0	670.4	0	136.1	390.1
3	2231.3	2118.0	275.8	8.4	668.5	0	578.0	0	587.3	113.3
4	1351.9	1319.0	1006.2	7.9	0	0	0	0	304.9	32.9
5	1498.5	1328.8	112.9	0	613.2	0	602.7	0	0	169.7
6	3088.5	2858.8	944.3	0	0	123.4	1151.2	0	639.9	229.7
7	1797.5	1687.5	683.6	0	0	0	766.7	0	237.2	110.0
8	1256.0	1256.0	0	0	0	0	949.7	0	306.3	0
9	926.5	926.5	881.1	0	0	0	0	0	45.4	0
10	1248.5	1113.3	205.5	93.9	0	64	419.5	0	330.4	135.2
11	1614.0	1300.2	434.0	18	0	479.6	16.9	0	351.7	313.8
12	1655.5	1179.0	456.9	9	0	0	403.1	0	310.0	476.5
13	2813.1	2416.0	1548.5	131.8	0	0	0	0	735.7	397.1
14	1620.5	1620.5	315.4	0	0	268.3	696.7	0	340.1	0
15	1592.8	1111.3	650.1	0	149.6	0	0	0	311.6	481.5
16	2518.1	1803.8	792.7	41.8	225.8	0	378	0	365.5	714.3