Ethanol production from cereal food waste – an enriched carbohydrate source

by

Moises Maldonado Gutierrez

B.S., University of California, Riverside, 1996

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2019

Approved by:

Co-Major Professor
Dr. Larry E. Erickson

Approved by:

Co-Major Professor
Dr. Bin Liu

Copyright

Abstract

Our planet is facing several environmental problems including air and water pollution, and global climate change. With all these problems to deal with, the natural resources of the Earth are starting to become scarce. Some solutions and initiatives are beginning to be adopted to address the irreversible damage that it is being done to the planet. However, the problem of food waste is one that affects the population of the world in many ways including environmental damage and not much has been done to mitigate its impact. The biodegradation of food generates gases such as methane and carbon dioxide that pollute air and water; especially if there is not a control to dispose of food waste.

Renewable fuels have become a potential solution to substitute for fossil fuel and lessen the damage being done to the planet, and ethanol is one of these promising fuels. Ethanol is produced biochemically through the fermentation of simple sugars; nowadays, this method constitutes the primary source to make the alcohol. Ethanol is produced mainly from the hydrolysis and fermentation of starch and the sugars contained in corn grain and sugar cane. Consequently, the use of these foods has triggered socio-economic conflicts affecting modern society such as the rise in the price of food and the dilemma of fuel vs. food. However, it has also led to new research on other sources of raw materials to produce ethanol such as food waste and cellulose, among others.

This review aims to highlight the advantages of turning food waste into useful fuels while alleviating environmental concerns. First, ethanol could be produced from food waste, especially cereals since they are rich in carbohydrates and are one of the most wasted foods. Second, pollution effects could be reduced by redirecting food waste from landfills into ethanol production. Third, the socioeconomic impact caused by using edible food products to produce ethanol could be allayed.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I want to express my gratitude and thank my supervisory committee Dr. Bin Liu, Dr. Sigifredo Castro, Dr. James Edgar and particularly to Dr. Larry Erickson for his guidance, suggestions and continuous support received during this time. I want to thank the Chemical Engineering faculty for all teaching and support given during the academic experience. Most importantly, I want to thank my family, particularly, my wife for all her love and support during all these years.

Dedication

I dedicate this work to my father's memory, Moises Gutierrez Sr. (1939-2018), for all his teachings, his support and for teaching me to be who I am, and also, to my wife Azucena for all her support and love, my children, Ariadne, Axel, and Alexa, and my mother, Delia.

Chapter 1 - Introduction

1.1 Background

Environmental pollution concerns such as air pollution, water pollution, and solid waste management are some of the reasons for finding alternative fuels. Biorefineries have become a solution to energy and environmental concerns, developing and driving the use of alternative and renewable fuels. Among the renewable fuels, ethanol is considered one of the most sustainable and renewable fuels that can replace fossil fuels (Pietrzak and Kawa-Rygielska, 2014).

Ethanol is usually produced by microbial fermentation using plant biomass as a raw material. Manufacturing ethanol from agricultural products has been in development for years, and it can be produced from many kinds of raw materials that contain a high concentration of sugar, starch, or cellulose. Among the most used bioenergy crops to produce ethanol, sugarcane is the primary raw material in tropical countries such as Brazil and India. In North America and Europe, ethanol is obtained from the starch present in corn and cereals (Cardona et al., 2005). Nevertheless, fuel production from cereal resources has affected the prices of food products manufactured from them (Pietrzak and Kawa-Rygielska, 2014).

Agriculture commodity prices usually are driven by the economic model of supply and demand. However, there are cases where agricultural produce prices move all together, particularly when responding to some generalized shift in supply or demand such as prolonged drought or the rising food demands in developing countries. Often, when important macroeconomic factors are involved such as rapid economic growth or

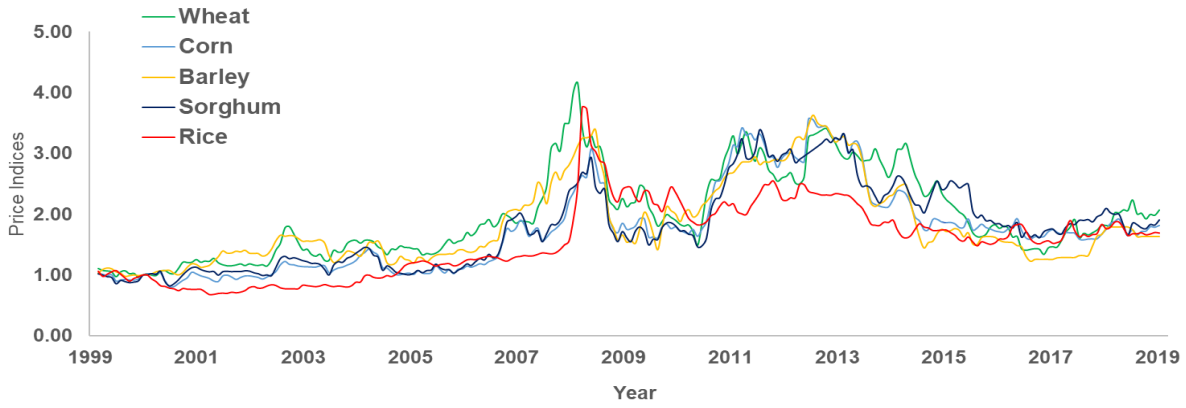

Figure 1.1 Cereal commodity price indices 1999–2019 (2000 =1)

Source: Indexmundi, (2019)

decline, as it occurred in 2009, many agricultural commodity prices do move together Figure 1.1 (Tyner, 2013). According to the US Department of Agriculture (USDA), from the total corn grain harvested in 2011, more than 40% was processed to produce ethanol while the remaining part went to livestock feed, food, and industrial uses, and was exported as outlined in Table 1.1 (Mumm et al., 2014). Subsequently, the price of the agricultural commodities does not increase as the demand for ethanol raw material increases.

The use of non-edible parts of the plant known as lignocellulose biomass is considered as the most promising opportunity for ethanol production that does not affect the prices of food products. Nevertheless, the conversion of lignocellulosic biomass into fermentable sugars and, then into ethanol requires high-temperature pretreatment which is often catalyzed using corrosive, non-ecological or costly processes (Pietrzak and Kawa-Rygielska, 2014). Furthermore, the efficiency of saccharification and fermentation of lignocellulose is still much lower in comparison to starches, but starchy raw materials are very costly, and the cost of the feedstock can exceed 65% of the price of the final

product (Pietrzak and Kawa-Rygielska, 2014). One solution to the problems of a possible increase in food prices due to crops being used for biofuel production and the difficulties with the use of lignocellulosic biomass is the use of food wastes for the manufacture of ethanol.

1.2 Food Waste as an Alternative

With one-third of all produced food being wasted (FAO, 2011), food waste may well be considered one of the lost energy streams. Cuellar and Webber (2010), estimated the energy embedded in the United States wasted food represents approximately 2% of the annual energy consumption in the United States, which is significant. Furthermore, food is not only a form of energy, but it is a consumer of energy in its production, preparation, transportation, and distribution. In 2010, it was estimated that 15.7% of the US energy consumption in 2007 was used to produce food. Therefore, energy discarded in food waste is more than the energy available for efficiency and energy procurement strategies, including the production of ethanol from agriculture products (Cuellar and Webber, 2010).

Table 1.1 Disposition (%) among major uses of corn harvested in the US in 2011

Category	Percentage
Ethanol	40%
Livestock feed	37%
Food & Industry	11%
Export	12%

Source: Mumm et al. (2014)

Table 1.2 Supply chain waste in food system by category

Category	Percentage
Consumption	21%
Distribution	13%
Processing	12%
Post-harvest	21%
Agriculture	33%

**** Source: Baldwin, (2015)***

Food waste occurs on every stage of the food supply chain: agriculture, post-harvest, processing, distribution, and consumption (Table 1.2). Worldwide, 1.3 billion metric tons of food waste is generated annually, and it is estimated to increase in parallel with population growth (Hao et al., 2015). Additionally, it has been determined that 1.4 billion hectares of fertile land (28% of the world's agricultural area) are used annually to produce food that is lost or wasted (Paritosh et al., 2017). Besides the magnitude of the wasted food quantity, it also represents a severe pollution problem and requires proper waste management techniques. Conventionally, food waste, which in the United States represents a 14.5% component of municipal solid waste (EPA, 2013), is landfilled or incinerated. When buried in a landfill, food waste decomposes primarily generating methane, a greenhouse gas with a global warming potential higher than carbon dioxide. It has been estimated that 125 m^3 of gas is produced from each ton of wasted food disposed of in a landfill, with an average composition of 35%-40% carbon dioxide and 60-65% of methane which accounts for 8% of the total anthropogenic methane emissions (Matsakas and Christakopoulos, 2015). Even though there are landfills where the generated methane is often used as an energy source, landfills continue to be assessed as the second largest source of anthropogenic methane in the United States due to fugitive emissions and emissions before the installation of gas collection systems (Levis and Barlaz, 2011).

Incineration of waste can generate energy, but operation cost and environmental issues are associated with this waste treatment practice. Due to high moisture content, food waste burns inefficiently during incineration, leading to other environmental and air pollution problems (Paritosh et al., 2017). Additionally, incineration diminishes the value of the biomass as it deters the recovery of nutrients and valuable chemical compounds. Other waste treatment practices are the use of food waste for feeding animals raising hygiene-related issues, and the use of them as fertilizers causing water pollution problems. (Matsakas and Christakopoulos, 2015). In summary, despite the disposal method used, the carbon footprint of food waste is estimated to contribute to greenhouse gas (GHG) emissions by accumulating approximately 3.3 billion tons of carbon dioxide into the atmosphere per year (Paritosh et al., 2017).

Traditional food waste disposal methods are challenging from the environmental and sustainability point of view and do not help with the reduction of environmental problems. On the other hand, food waste is rich in carbohydrates, proteins, and minerals, making it an exceptional raw material for bioethanol production by fermentation and replacing agriculture products as the raw material.

The advantage of using food waste in the fermentation process to produce ethanol not only solves the issue of producing alternative fuels but improves current practices such as:

- The “food versus fuel” dilemma and its economic impact.
- Reduction in the use of landfill areas.
- Minimizing greenhouse gas emissions.
- Preventing water pollution.
- Refining land use.

Fermentation-based approaches are widely used either on their own or in combination with other treatment technologies for processing of food waste, mainly to: (i) maximize recycling of nutrients/energy and (ii) reduce treatment cost, time requirements, and environmental problems (Hao et al., 2015). Food waste mainly consists of carbohydrates, proteins, lipids, and minerals. The composition differs depending on the type of food waste and its constituents. Cereal, vegetables, and fruits are high on carbohydrates, while meat, fishery, eggs are high in proteins and lipids. However, wasted food from the consumption category, which is generated at household and food service, consisted mainly of a mixed food component (Table 1.3).

One of the most promising wastes that can be processed into ethanol is cereal waste which includes bakery waste, bread waste, corn product waste, wheat product waste and any by-product from cereal processing. Cereal waste contains a significant amount of starch that is easily hydrolyzed to monomeric sugars using amylases and contains protein which, after hydrolysis to peptides and amino acids, is essential for yeast growth and enhanced fermentation.

Table 1.3 Characteristics and chemical composition of kitchen food waste

Component	Percentage	Chemical	Composition
Total Carbohydrates	41-54%	C	46.1~48.1%
Crude Protein	20-25%	H	6.8~7.2%
Crude Lipids	5-15%	O	32.4~36.7%
Crude Fiber	5-17%	N	3.5~4.1%
Ash	5%	Cl	1.9~2.2%

**** Weight percentage based on dry food wastes***
Source: Kim et al., (2011)

Chapter 2 - Ethanol from Food Waste

2.1 Food waste and Ethanol in Numbers

Ethanol has been produced since ancient time, primarily as an alcoholic beverage. Currently, ethanol is mainly produced from the fermentation of renewable raw material, and it has become the primary alternative biofuel, used as an additive for gasoline with the possibility of becoming the fossil-fuel replacement. The demand and supply of ethanol have increased dramatically in the last two decades, indicating the growing need for an oxygenating agent for gasoline and flex fuel for transportation (Trabold and Babbitt, 2018). Hence, by 2017, global production of ethanol reached 27 billion gallons with the United States and Brazil producing 58% and 26% of the world production, respectively. Whereas, the rest of the world produces only 16% as shown in Table 2.1 (RFA, 2019). In the United States, the world's largest producer, ethanol production has significantly increased in the period 2000-2017 from 1,622 to 15,845 million gallons per year as illustrated in Figure 2.1 (RFA, 2019). Also, in the United States, currently, there are a total

Table 2.1 Global ethanol production (2014-2017) in millions of gallons

Region	2014	2015	2016	2017
United States	14,313	14,807	15,413	15,845
Brazil	6,190	7,093	7,295	7,060
European Union	1,445	1,387	1,377	1,416
China'	635	813	845	875
Canada	510	436	436	450
Thailand	310	334	322	395
Argentina	160	211	264	310
India	155	211	225	280
Rest of the world	865	391	490	465
World	24,583	25,683	26,667	27,096

**** Source: RFA, (2019)***

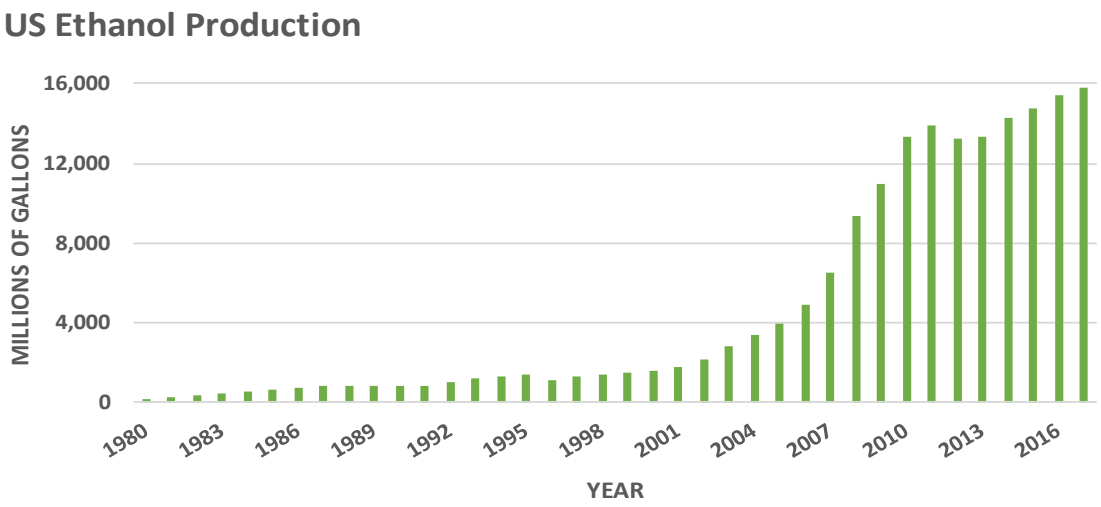

Figure 2.1 Annual US Ethanol Production 1980–2017 in millions of gallons

Source: RFA. (2019)

Table 2.2 Percent of share of feedstock in total US Ethanol production (2017)

Category	Percentage
Corn	95%
Co-fermentation	3%
Biomass	1%
Food Waste	1%

**** Trabold and Babbitt, (2018)***

of 204 operating ethanol plants located mainly in the so-called Corn Belt in the Midwest geographical area (Figure. 2.2).

Ethanol produced in the United States, generally, is made by the fermentation of rich carbohydrate material, precisely, corn grain where in 2016 38% of corn production was used for ethanol production, compared to 12.4% in 2006 (Trabold and Babbitt, 2018). Nonetheless, a high percentage (97%) of US bioethanol plants continue, principally, using corn as a feedstock, accounting for 94% of the alcohol production; whereas only less than 1% of the ethanol production comes from seven food waste processing plants as outlined in Table 2.2 (EPM, 2019). However, it is important to note that most of the seven plants

are not entirely independent biorefineries, but as a subdivision of a current food processing plant, designed to treat the food waste generated on site. Table 2.3 outlines the information, feedstock, and capacity of each of the food waste plants in the United States. Despite the low production and capacity to produce ethanol from food waste, there is a remarkable research effort to understand the process of converting food waste into renewable fuels, mainly cereal food waste that is rich in carbohydrates.

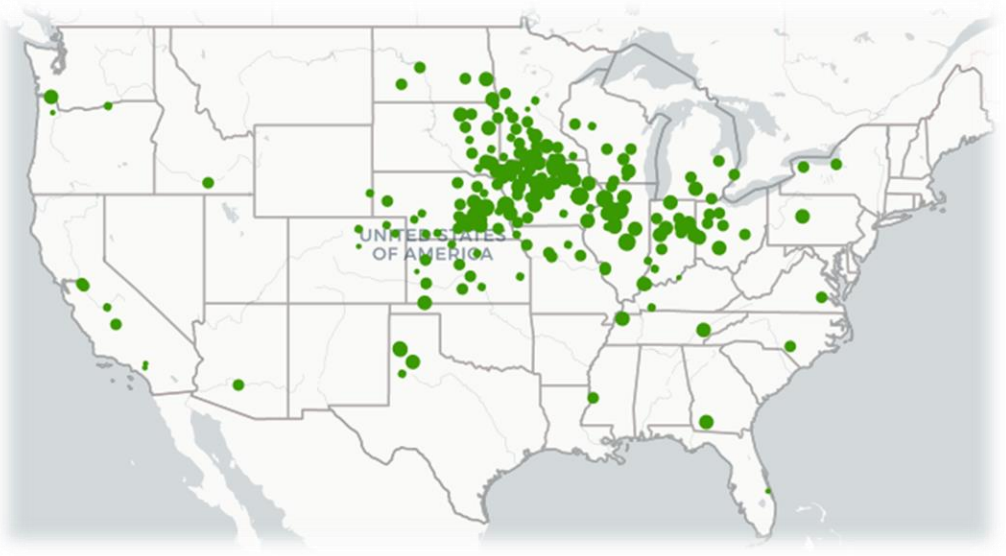

Figure 2.2 Location of the US Ethanol Plants

Source: NREL, (2019)

Table 2.3 US Ethanol Plants using Food Waste as a Feedstock (in millions of gals/year)

Company Name	Location	Feedstock	Plant Capacity
POET-DSM Advanced Biofuel	Emmetsburg, IA	Crop residue	20.0
DuPont Cellulosic Ethanol,	Nevada, IA	Crop residue	30.0
Summit Natural Energy, Inc.	Cornelius, OR	Fruit processing waste	1.0
Red River Biorefinery LLC	Grand Forks, ND	Sugar beet waste	17.0
Parallel Products of Kentucky	Louisville, KY	Waste beverage	6.0
Parallel Products of California	Rancho Cucamonga, CA	Waste beverage	1.5
Merrick/Coors	Aurora, Co	Waste beer	3.0

**** Source: EPM, (2019)***

2.2 Cereal Food Waste as a Feedstock

Similarly, to ethanol, cereals have been harvested since ancient times and have been the most primary food supply for civilizations. Nowadays, they continue to be the largest food group and one of the main nutritious foods. In 2017, worldwide cereal production approximated three billion tons (Table 2.4) and accounted for more than half of all the food eaten by humans and fed to animals (FAO, 2019). However, the cereal wastage, correspondingly, has gotten into a high level as well, and by 2011, the food waste percentage originated from cereals was at 29% (FAO, 2011), generating a suitable raw material for ethanol production.

The organic composition plays a crucial role in food waste fermentation and valorization, which is the economic transformation of goods into alternative fuels, energy, and other useful chemicals, with specific attention for sustainability and environmental objectives (ElMekawy et al., 2013). Thus the cereal-based food waste is not an exception, and its composition is vital for possible fermentation. Nutrients stored in macromolecules such as complex carbohydrates, in the form of starch, and proteins must be converted

Table 2.4 World and US cereal production (2017) in millions of tons per year

Region	World	US
Barley	147.4	3.1
Corn	1,146.5	375.0
Millet	28.5	0.3
Oats	25.9	0.7
Rice	769.7	8.1
Rye	13.7	0.2
Sorghum	57.6	9.2
Wheat	771.7	47.4
Other	7.0	
World	2,968.0	444.1

**** Source: FAO. (2019)***

into utilizable smaller molecules like sugars and amino acids, respectively to facilitate microorganism growth. Nevertheless, the nutritional composition of cereal-based waste varies depending on the prior handling or processing of waste. Even though the composition of cereal process waste is nearly similar to its original flour or raw material, the processes of hydrolyzing flour and heating grain might vary with the composition due to structural changes resulting from dough production and baking (Ebrahimi et al., 2008). Several researchers have analyzed the composition of cereal food waste (Table 2.5), and typically, the composition for dry weight mass contains 650-800 $g\text{-}kg^{-1}$ of carbohydrates, which 500-750 $g\text{-}kg^{-1}$ might be in the form of starch, 90-140 $g\text{-}kg^{-1}$ of crude protein and 20-50 $g\text{-}kg^{-1}$ of fat content.

Glucose and other simpler sugars are readily converted from starch; however, even though a higher reduced sugar content is preferred in ethanol production, high sugar concentrations inhibit ethanol production by affecting microbial metabolism. Therefore, during fermentation, food waste substrate should have a 15%-20% of free sugar concentration (Trabold and Babbitt, 2018). If it does not contain the required, reducing sugar concentration, a pretreatment is essential to transform complex sugars into simpler monosaccharides and oligosaccharides. Additionally, it is also significant to maintain a balance between carbohydrates and proteins. A ratio of carbohydrates to proteins can be translated into a carbon/nitrogen (C/N) ratio since proteins are rich in nitrogen source. Some researchers use the Merrill and Watt factor to calculate the percent of protein (Merrill and Watt, 1955)

$$\% \text{ Protein} = \% \text{ FAN} * 5.7 \qquad (2.1)$$

where FAN is the free amino nitrogen. High FAN concentration is essential for fermentation of sugars as it delivers a balanced nitrogen source for cell growth and

metabolism. However, nitrogen excess could form ammonia and inhibit the biological process (Paritosh et al., 2017). The role of organic carbon and inorganic nitrogen are substantial for cell synthesis and metabolism. Hence, the available amounts of each element are crucial; a C/N ratio range of 25 to 30 has been determined to be an ideal ratio. A feedstock with a C/N ratio greater than 30 is considered deficient in nitrogen for a good biological process (Kiran and Liu, 2015; Tanimu et al., 2014).

Several studies show an increase of productivity by co-fermentation of different food waste streams; for example, when corn starch was co-fermented with soy skim milk, ethanol production increased from 18% to 25% (Trabold and Babbitt, 2018). Also, Kumar et al., (1998) reported an ethanol yield increase from 33% to 36% and a reduced fermentation time from 60 hours to 12 hours when bread waste was co-fermented with cheese whey. Moreover, it was also noticed that ethanol concentration increased as the metal ion concentration increased up to a point, and after that, the ethanol yield decreased with any addition of metal ions (Kumar et al., 1998). Metal ions are essential elements of the inorganic content of cereal food waste and are vital to the metabolism of the microorganisms. Therefore, the increase of ethanol yield is described by the fact that microorganisms use metal ions as stabilizing agents and nutrients during the growth phase (Kumar et al., 1998).

Deficiency and overload of metal ions can damage microorganisms and create a reversion on the overall production yield (Trabold and Babbitt, 2018). It is essential to remark that cereal food waste composition may vary with time of year, location, collection and storing conditions. Subsequently, a physical-chemical property monitoring system for feedstock is requisite for a suitably-designed fermentation process.

Table 2.5 Reported composition analysis of different cereal food wastes in percentage of wet mass

Type of waste	Moisture	Starch	Carbohydrates	Protein	Crude Fiber	Ash	Fat	Total Organic Nitrogen	Phosphorus	Reference
Waste Bread	22.30	59.80	*NR	8.90	*NR	*NR	*NR	1.56[a]	Trace	Leung et al., 2012
Waste bread	24.30	64.06	*NR	9.00	*NR	2.30	*NR	1.50[a]	0.08	Han et al., 2017
Waste Bread	37.00	47.00	50.00	8.00	*NR	2.26	*NR	1.61[a]	0.10	Melikoglu and Webb, 2013
Waste Bread	27.00	56.30	64.10	8.50	3.10	*NR	*NR	*NR	*NR	Adessi et al., 2018
Wheat/Rye bread waste	26.26	51.17	*NR	*NR	*NR	*NR	*NR	*NR	*NR	Kawa-Rygielska et al., 2012
Wheat waste	8.00	67.50	71.70	13.70	*NR	*NR	*NR	*NR	*NR	Vidmantiene et al., 2006
Wheat Flour	*	*NR	73.20	13.90	*NR	1.50	2.40	*NR	0.30	Dewettinck et al., 2008
Rye waste	*	59.80	73.80	11.70	*NR	*NR	*NR	*NR	*NR	Vidmantiene et al., 2006
Cake waste	*	48.50	64.30	14.10	*NR	3.90	*NR	*NR	*NR	Kiran & Liu., 2015
Corn meal	3.91	70.82	*NR	11.80	*NR	5.58	7.89	*NR	*NR	Mojovic et al.,2006
Corn meal	*	76.89	*NR	*NR	*NR	*NR	*NR	*NR	*NR	Lei et al., 2014
Rice flour waste	5.00	*NR	*86.10*	*7.30*	*NR	*NR	*1.10*	*NR	*NR	Lin et al., 2013
Corn waste	11.69	70.83	*NR	9.33	*NR	1.47	3.94	*NR	0.29	Fung et al., 2018
Corn Waste	6.50	75.00	*NR	9.40	1.60	2.12	*NR	*NR	*NR	Meenakshi and Kumaresan, 2014
Corn Flour	*	74.90	76.60	8.80	*NR	1.70	4.40	*NR	*NR	Manikandan & Viruthagiri, 2010
Corn	15.50	60.59	*NR	8.69	*NR	1.18	3.64	*NR	*NR	Cardona et al., 2005

**** Reported as Dry Mass***

****NR Not Reported***

[a] Used Merrill & Watt factor to calculate the % of protein. Protein= % Nitrogen * 5.7 (Merrill & Watt, 1955)

Chapter 3 - Description of the Ethanol Process

3.1 Feedstock Preparation

It has been specified before that cereal food waste contains macromolecules rich in carbohydrates and protein, and they must be available for enzymatic hydrolysis to extract the simpler sugars. Hence, reducing particle size can become a substantial process step in the extraction of nutrients and for efficient fermentation. Several studies involving cereal food waste as the feedstock have been conducted, and they have reported a high yield when particles sizes were less than 1 cm (Table 3.1). The particle size is also an essential step for other fermentation processes such as corn ethanol. Naidu et al., (2007), reported a 12.6% (v/v) concentration yield from a 0.5 mm corn particle size; a significant increment when a 5 mm corn particle size yielded a 1.62% (v/v) concentration.

The process efficiency is positively affected by reducing the particle size. The smaller sizes increase the soluble solids, and the mass transfer of nutrients for microorganisms is simplified. Therefore, a particle size < 3 mm is recommended for cereal food waste, if not, nutrients are not exposed to microorganism activities, leading to incomplete conversion and low process efficiency (Trabold and Babbitt, 2018).

It should also be noticed that food waste is substantially vulnerable to spoilage, mold growth and impurities derived from a process. Mold growth encourages the consumption of valuable substrates and the release of heat-resistant mycotoxins that contaminate the feedstock and affect the overall process efficiency negatively (Ebrahimi et al., 2008). Generally, molds are heat-sensitive, and pasteurization above 70-80 °C is

enough to inactivate spoiling activity (Samson et al., 2004). Hence, a heat treatment is advisable to neutralize any mold growth in the feedstock and prepare it for the enzymatic hydrolysis.

3.2 Enzymatic Hydrolysis and Saccharification

Starch consists of glucose molecule chains linked together by 1-4-α-glucosidic and 1-6-α-glucosidic bonds. The linear starch chains linked by the 1-4-α-glucosidic bonds are known as amylose, while 1-6-α-glucosidic bonds create branched chain known as amylopectin. Furthermore, starch chains cannot be metabolized by yeast; thus, the starch needs to be hydrolyzed to release glucose molecules. Typically, the hydrolysis of starch consists of a two-step method: enzymatic hydrolysis and saccharification. The first step is also known as liquefaction, and it consists of breaking down the by 1-4-α-glucosidic bonds in the middle of amylose and amylopectin chains and forming short-chain dextrins. In the second step, saccharification, the remaining 1-4-α-glucosidic bonds, and 1-6-α-glucosidic bonds are broken down, and at the same time, dextrins are saccharified to yield monomeric sugars (Pietrzak and Kawa-Rygielska, 2014).

The enzymatic hydrolysis starts with the feedstock heating which provides the high temperature and the mechanical shear necessary to cleave and rupture starch molecules, particularly those with a high molecular weight (Bothast and Schlicher, 2005). Additionally, with a heat treatment, the starch structure does gelatinize, enabling the enzyme to access and digest the polymer and create a viscous substrate (Meenakshi and Kumaresan, 2014). Research studies have been conducted on food waste fermentation and have reported the glucose yield by liquefaction and saccharification processes (Table 3.1). However, in order to achieve liquefaction, substrate parameters must be set and

controlled. First, the pH must be adjusted to 6.0, followed by addition of the stable thermal enzyme targeting 1-4-α-glucosidic bonds. After the enzymes are added, the temperature needs to be set to 80-90 °C usually done by a jet cooker to improve the flowability of the substrate. Also, jet cooking serves as a sterilization step to avoid microorganism contamination. Regularly, the liquefaction is a rapid process, and 0.5-2.0 hours should be sufficient time for the purpose, as long as the conditions are met, and the right dose of the enzyme has been applied.

The enzymatic dosage might vary depending on the type and the concentration of the enzyme. In starchy food waste fermentation, α-amylase is commonly used and advisable due to the high-temperature conditions (Table 3.2). An additional type of enzymes can be used for liquefaction. Kim et al., (2011) used carbohydrase, a mixture of enzymes composed of arabinase, cellulase, β-glucanase, and xylanase, for the liquefaction of kitchen food waste to extract sugar molecules from starchy and cellulosic materials with a high glucose yield of 0.83 g/g of total solid.

Meanwhile, to complete the release of simpler sugar molecules, the mash or substrate should go thru a saccharification process. Similarly, to liquefaction, saccharification requires a process parameter to be met and under control. The substrate must be cooled down to a 55- 60 °C and the pH is adjusted to 4.5-5.0. However, saccharification is a slow process and requires 2-4 hours to be complete with the right dose of enzymes. Recalling that it is in the saccharification process where mainly the 1-6-α-glucosidic bonds and the short dextrin chains are broken, the enzyme used in this process must cleave such bonds and chains. In starchy food waste, glucan 1,4-α-glucosidase is the enzyme commonly used for this purpose, and this dosage depends on its concentration and the process conditions (Table 3.2).

Liquefaction and saccharification are costly processes. A significant demand for energy is required due to the high temperature in liquefication and to the slow action of the glucan 1,4-α-glucosidase enzyme. Therefore, the need for energy optimization led to the development of simultaneous saccharification and fermentation (SSF) process, in which liquefied starch slurry is cooled down to a temperature where yeast can ferment, and the saccharification enzymes added. Consequently, the saccharification of dextrins and utilization of the resulting monomeric sugars occurs at the same time (Pietrzak and Kawa-Rygielska, 2014). Furthermore, Pietrzak and Kawa-Rygielska, (2014), reported an ethanol conversion from waste bread of 80% following an SSF process and an ethanol conversion of 87% resulting from a separate hydrolysis and fermentation (SHF) process. Finally, it should be remarked that the thermal heating process may lead to partial degradation of sugars and other nutrients and to side reactions in which the amounts of useful sugars and amino acids are reduced. (Trzcinski, 2018). The simultaneous saccharification and fermentation process could be the solution to overheating issues.

Table 3.1 Process parameters for feedstock pretreatment, enzymatic process, and saccharification

Type of Waste	Feedstock Pretreatment	Enzymatic Hydrolysis		Saccharification		Sugar Conversion Sugar Concentration(g/L) or Sugar Yield (g/gTS)	Reference
		Enzyme	Process Parameters	Enzyme	Process Parameters		
Kitchen Food Waste	Sterilized for Temp 121 °C Time 15 min	Carbohydrase	Dosage 30 ml/ 3 L Temp 35° C pH 4.5 Time 12 h	Glucoamylase	[a] Dosage 30ml/ 3 L Temp 35 °C pH 4.5 Time 48-72 h	135 g/L 0.83 g /g TS	Kim et al., 2011
Kitchen Food Waste	Ground Sieved Storage at - 20° C	Glucoamylase	[c] Dosage 7.7 g/ 180 g Temp 60° C pH 4.0- 4.5 Time 24 h	ND	ND	127 g/L	Kiran et al., 2015
Bread Residues	Powdered Sized Storage at - 20° C	α-Amylase	Dosage 8 ml/ kg Temp *NR* pH 6.0 Time *NR*	Amyloglucosidase	Dosage 8 ml/ kg Temp 60° C pH 4.5 Time *NR*	250 g/L	Ebrahim et al., 2008
Bakery Waste	-Ground to fine powder -Hot water	α-Amylase	Dosage 1.0 ml/ L Temp 70° C pH 5.0 Time 2 h	Amyloglucosidase	Dosage 1.0 ml/ L Temp 55° C pH 4.5 Time 4 h	0.61 g/g TS	Kumar et al.,1998
Waste Bread	Dice 1 cm^3 autoclaved 15 min	α-amylase	[d] Dosage *NR* Temp 55° C pH 5.0 Time 2 h	ND	ND	0.47 g/g TS	Leung et al., 2012
Waste bread	[f] Ground >1 cm Temp 90 °C Time 15 min ratio 1:5(w/v)	Protease, and Glucoamylase	Dosage *NR* Temp 55° C pH NR Time NR	ND	ND	26.05 g/L 0.521 g/g TS	Han et al., 2017
Waste bread	Dice 2-4cm pH 6.0 Temp 40 °C Time 12h Ground 1.5mm	α-Amylase,	Dosage 1.25g / kg Temp 45° C pH 4.50 Time 0.33 h	Protease, and Glucoamylase	Dosage 1.25 & 0.875 ml/ kg Temp 55° C pH 5.8 Time 1.5 h	102 g / L	Pietrzak et al., 2014
Wheat/Rye bread waste	Dice 1cm pH 6.0 Temp 45 ° Time 0.33 h	α-Amylase and β-Glucoamylase	Dosage 0.4 ml Temp 85° C pH NR Time 1 h	α-Amylase, β-Glucanase, Protease, Cellulase, and Pentosanase	[a] Dosage 0.4 ml Temp 55 °C pH 5.8 Time 1.5 h	122 g/L	Kawa-Rygielska et al., 2012

Table 3.1 Process parameters for feedstock pretreatment, enzymatic process, and saccharification-cont'd

Type of Waste	Feedstock Pretreatment	Enzymatic Hydrolysis		Saccharification		Sugar Conversion Sugar Concentration(g/L) or Sugar Yield (g/gTS)	Reference
		Enzyme	Process Parameters	Enzyme	Process Parameters		
Wheat & Rye waste	[f] Ground >1 cm Temp 90 °C Time 15 min ratio 1:5(w/v)	α-Amylase,	Dosage *NR* Temp 65° C pH 6.0-6.5 Time 1.5 h	β-Glucanase, β-Xylanase, cellulase	Dosage 1.25 & 0.875 ml/ kg Temp 55-60 ° C pH 5.0-6.0 Time 2 h	N/R	Vidmantiene et al., 2006
Corn meal (food waste)	Milled 90% 05-1.0 mm 10% <0.5mm	α-Amylase	Dosage *1.3 % w/w* Temp 85° C pH 6.0 Time 1 h	Amyloglucosidase	[e] Dosage *1.3 % w/w* Temp 55° C pH 5.0 Time 4 h	[b] 94%	Mojovic et al., 2006
Corn meal	Slurry 20% w/w	α-Amylase (5 U/g)	Dosage *5* µg/g Temp 90° C pH 4.8 Time 0.55 h	Glucoamylase (37.5 U/ml)	Dosage *37.5* µg/g Temp 50° C pH 4.8 Time 5 h	100.5 g/L	Lei et al., 2014
Corn Waste	0.104, 0.157 & 0.211 mm Temp 121 °C Pressure 15 psi Time 30 min	α-Amylase (579 U/g)	[g] Dosage 0.08g/g Temp 90° C pH 6.0 Time 2 h	Glucoamylase (1346 U/ml)	[a] Dosage NR Temp NR pH NR Time 48-72 h	100.5 g/L	Meenakshi and Kumaresan, 2014
Corn Flour	Slurry 25% w/v Pressure 15 psi Time 60 min	α-Amylase (130 lU/g)	Dosage *2g* Temp 70° C pH 6.0 Time 2 h	Amyloglucosidase	[a] Dosage NR Temp NR pH NR Time 48-72 h	N/R	Manikandan and Viruthagiri, 2010
Corn	Size 3-5 mm Temp 110 ° C	α-Amylase	Dosage *NR* Temp 88° C pH 4.0-5.0 Time *NR*	N/D	[a] Dosage NR Temp NR pH NR Time NR	N/R	Cardona et al., 2005

NR Not reported, N/D No Data

[a] Simultaneous Saccharification & Fermentation Process

[b] Yield reported in percentage

[c] pH was not controlled and reaction was mixed at 500 rpm

[d] pH was not controlled and reaction was mixed at 300 rpm

[e] Reaction was mixed at 150 rpm

[f] Preheated for partial degradation of starch and reduction of microorganism activity

[g] pH adjusted with 3N NaOH or 3N orthophosphoric acid and reaction was mixed at 150 rpm

Table 3.2 Commonly used enzymes in food waste hydrolysis.

Enzyme	ECN	Alternative Name(s)	Action	Comments
α-Amylase	3.2.1.1	glycogenase endoamylase **4-α-D-glucan glucanohydrolase**	Endohydrolysis of (1-4)-α-D-glucosidic linkages in polysaccharides containing three or more (1-4)-α-linked D-glucose units.	Acts on starch, glycogen and related polysaccharides and oligosaccharides in a random manner; reducing groups are liberated in the α-configuration.
β-Amylase	3.2.1.2	glycogenase saccharogen amylase **4-α-D-glucan maltohydrolase**	Hydrolysis of (1-4)-α-D-glucosidic linkages in polysaccharides so as to remove successive maltose units from the non-reducing ends of the chains.	Acts on starch, glycogen and related polysaccharides and oligosaccharides producing β-maltose by an inversion.
γ-amylase	3.2.1.3	glucoamylase amyloglucosidase glucose amylase **4-α-D-glucan glucohydrolase**	Hydrolysis of terminal (1-4)-linked alpha-D-glucose residues successively from non-reducing ends of the chains with release of beta-D-glucose.	Most forms of the enzyme can rapidly hydrolyses 1-6-α-D-glucosidic bonds when the next bond in the sequence is 1-4, and some preparations of this enzyme hydrolyses 1-6- and 1-3-α-D-glucosidic bonds in other polysaccharides..
Cellulase	3.2.1.4	endo-1,4-β-D-glucanase β-1,4-glucanase **4-β-D-glucan 4-glucanohydrolase**	Endohydrolysis of (1-4)-β-D-glucosidic linkages in cellulose, lichenin and cereal β-D-glucans.	Will also hydrolyse 1-4-linkages in β-D-glucans also containing 1-3-linkages.
β-Xylanase	3.2.1.8	endo-1,4-xylanase β-1,4-xylanase endo-1,4-xylanase **endo-1-4-β xylanase**	Endohydrolysis of (1-4)-β-D-xylosidic linkages in xylans.	
Pullulanase	3.2.1.41	amylopectin 6-glucanohydrolase α-dextrin endo-1,6-α-glucosidase **pullulan 6-α-glucanohydrolase**	Hydrolysis of (1-6)-α-D-glucosidic linkages in pullulan, amylopectin and glycogen, and in the α- and β-limit dextrins of amylopectin and glycogen.	Its action on glycogen, and its rate of hydrolysis of limit dextrins. Its action on amylopectin is complete. Maltose is the smallest sugar that it can release from an α-(1-6)-linkage.
Lactase	3.2.1.108	lactase-phlorizin hydrolase **lactose galactohydrolase**	lactose + H_2O = D-galactose + D-glucose.	The enzyme from intestinal mucosa is isolated as a complex that it also catalyses the reaction of EC 3.2.1.62 glycosylceramidase

**** Source McDonald et al. 2009***

ECN = Enzyme Commission number

Systematic names are in bold.

3.3 Fermentation

The fermentative conversion is the heart of the process of transforming food waste into ethanol. The fermentation of food waste substrate is usually done by yeast specifically *Saccharomyces Cerevisiae*. Yeast is a facultative anaerobe and converts sugars into ethanol and carbon dioxide in the absence of oxygen; therefore, oxygen must be removed from the fermenter (Trabold and Babbitt, 2018). There are predetermined optimum conditions for the fermentation of the starchy substrate; however, caution should be taken when fermenting cereal food waste substrate due to the variations the hydrolysis and saccharification may create by the inconsistency of the raw material.

Yeast fermentation requires optimum conditions maintained during the process. Firstly, achieving a balanced pH is necessary for optimum fermentation. With a very high or low pH, the cells spend extra energy balancing the pH, reducing productivity. In cereal food waste, high fermentation yields have been obtained at a pH range of 4.5-6.0. Moreover, Meenakshi and Kumaresan (2014), reported in corn and potatoes peel waste fermentation study, that the yeast was capable of fermenting glucose best at an acidic environment, maximizing the ethanol yield at a pH of 5.5. Moreover, fermentation is an exothermic reaction, and extreme temperature can affect the fermentation process. High temperature causes yeast cells to die and changes the process. In the other hand, low temperature deactivates the cells which result in incomplete degradation of sugar into ethanol (Trabold and Babbitt, 2018). Typically, the temperature range used in food waste fermentation is from 30-35 °C (Table 3.3).

There is a concentration at which the glucose concentration is too high, and ethanol production is inhibited. Similarly, high ethanol concentration inhibits ethanol production. Therefore, both, glucose and ethanol concentrations, must be kept below 14-

18% (Probstein and Hicks, 1982); otherwise, the process becomes self-inhibitory. Additionally, fermentation, typically, requires 48-72 hours to complete the conversion.

Table 3.3 recapitulates previous studies of ethanol production from food waste, principally from cereal sources. The ethanol yield for cereal food waste fermentation has been published in a range from 0.20-0.48 g of ethanol per g of total soluble substrate. The highest yield stated, in Table 3.3, was by Yan et al., (2013) in pilot scale trial. Whereas, the lower yield was reported by Kim et al. (2011) in a continuous simultaneous saccharification and fermentation process. Likewise, the ethanol production rate was also reported by Pietrzak and Kawa-Rygielska, (2014), and the calculated value was 1.81 g/L-h ethanol production rate from waste bread. In a pilot plant trial, Yan et al., (2013) reported a 1.79 g/L-h ethanol production rate.

One way to increase ethanol yields is by increasing the mixing speed. At higher agitation speeds, the glucose uptake rate increases, and as a result, the fermentation of glucose is completed in a shorter time. Suitable agitation improves mass transfer and promotes cell growth, eventually increasing ethanol production. Kiran and Liu, (2015) reported, during the fermentation of food waste, a specific growth rate for 100 rpm of 0.24 h^{-1}, while for 200 and 300 rpm mixing speeds values of 0.30 and 0.32 h^{-1}, respectively. It was also reported in the same study that further increase in agitation speed beyond 200 rpm may not be helpful for ethanol production. As such, the highest ethanol concentration of 58 g/L was obtained at 200 rpm versus 57 g/L at 300 rpm (Kiran and Liu, 2015)

Finally, it is worth to mention that by-products such as methanol, iso-butanol, n-propanol, methyl acetate among other volatile organic compounds could be produced during the fermentation. However, as shown by Vidmantiene et al. (2006), applying an

enzyme complex (e.g., xylanase), the content of such by-products could be decreased thereby increasing the ethanol content in the distillate up to 2%.

3.4 Downstream processing – Distillation and Membranes Sieving

Downstream processing involves several unit operations to achieve the desired purity levels. Typically, ethanol concentration is 10-12% after the fermentation process; therefore, distillation columns are commonly used to remove the excess water and other by-products formed during the fermentation (Bothast and Schlicher, 2005). Conventional distillation concentrates ethanol to 95.6%; at this concentration ethanol and water form an azeotrope, and further dehydration of the alcohol needs to be done by other means. Current ethanol dehydration techniques include chemical reaction dehydration, azeotropic distillation, vapor permeation separation, and molecular sieving. Generally, the azeotropic distillation process is commonly used. However, molecular sieving is used as an alternative to azeotropic distillation due to the substantial amounts of energy required and the introduction of a third compound such as benzene or cyclohexane to break the azeotrope. For ethanol concentration purpose, aluminosilicate zeolite molecular sieves with a porosity of 30-40 nm are most widely used to achieve > 99.3% fuel grade purity (Chen et al., 2014).

3.5 Co-products - Distillers Grains and Carbon Dioxide

The solid and liquid remaining after distillation are known as distillers' grains, and they are composed of lipids, fibers, and proteins, along with the non-fermented starch. For instance, distillers' grains composition, from barley-based ethanol production, has 326 g-kg^{-1} of crude protein, 60 g-kg^{-1} fat content, 44 g-kg^{-1} ash and 166 g-kg^{-1} of crude

fiber (Mustafa et al., 2000). This co-product is a valuable feed ingredient for livestock, and other animal feeds. However, before selling it to animal feed, the thin stillage, 15-30% of the liquid fraction, is separated by centrifugation and recycled as backset. The remainder is concentrated and mixed with residual solid from the fermentation to form a viscous syrup known as the Wet Distillers Grains (WDG). In order to save transportation cost and to extend the shelf-life of the co-product, the wet distillers' product is dried from a 65% moisture to a 10-12% moisture creating dry distillers' product or Dried Distillers Grains (DDG), or simply it can be sold as WDG (Bothast and Schlicher, 2005).

Carbon dioxide is the third revenue product, and it is continuously produced during the fermentation process. The fermentation exhaust gas contains up to 99% of CO_2, which it needs further minor processing to remove the impurities (Trabold and Babbitt, 2018). The 2016 U.S. CO_2 market was estimated at 9.63 million short tons, and the ethanol industry supplied nearly 43% of the domestic CO_2, with many applications led by food and beverages and dry ice applications (Mueller, 2017).

Table 3.3 Process parameters for the fermentation of hydrolyzed food waste feedstocks

Type of Waste	Enzymatic Hydrolysis	Process Type	Fermentation Parameters		Concentration of EtOH (g/L)	Yield g EtOH/g TS	Production of EtOH g/l hr	Reference
			Fermentation Microorganism	Process Parameters				
Kitchen Food Waste	Carbohydrase	B-SHF	Saccharomyces cerevisiae	Volume 5 L Dosage NR Temp 35° C pH 4.5 Time 48 h	NR	0.43	1.18	Kim et al., 2011
Kitchen Food Waste	Carbohydrase	B-SSF	Saccharomyces cerevisiae	Volume 5 L Dosage NR Temp 35° C pH 4.5 Time 48 h	NR	0.31	0.30	Kim et al., 2011
Kitchen Food Waste	Carbohydrase	C-SHF	Saccharomyces cerevisiae	Volume 5 L Dosage NR Temp 35° C pH 4.5 Time 96 h	30.00	0.30	1.18	Kim et al., 2011
Kitchen Food Waste	Carbohydrase	C-SSF	Saccharomyces cerevisiae	Volume 5 L Dosage NR Temp 35° C pH 4.5 Time 120 h	21.00	0.20	0.80	Kim et al., 2011
Kitchen Food Waste	None	B-SHF	Saccharomyces cerevisiae	Volume 0.1 L Dosage 15 mg/g Temp 30° C pH 5.5 Time 21 h	5.98	NR	0.28	Matsakas and Christakopoulos, 2015
Kitchen Food Waste	Crude enzymes made on site	B-SHF	Saccharomyces cerevisiae	Volume 0.1 L Dosage 15 mg/g Temp 30° C pH 5.5 Time 21 h	19.27	NR	0.92	Matsakas and Christakopoulos, 2015
Kitchen Food Waste	Crude enzymes made on site	B-SHF	Saccharomyces cerevisiae	Volume 0.1 L Dosage 10% (v/v) Temp 30° C pH NR Time 32 h	58.00	0.33	1.82	Kiran and Liu., 2015
Bakery Food Waste	α-Amylase & Amyloglucosidase (Fungamyl)	B-SHF	Saccharomyces cerevisiae	Volume 2 L Dosage 2 g/L Temp 30° C pH 5.0 Time 12 h	NR	0.22	NR	Kumar et al., 1998

Table 3.3 Process parameters for the fermentation of hydrolyzed food waste feedstocks -cont'd

Type of Waste	Enzymatic Hydrolysis	Process Type	Fermentation Parameters		Concentration of EtOH (g/L)	Yield g EtOH/g TS	Production of EtOH g/l hr	Reference
			Fermentation Microorganism	Process Parameters				
Bakery Food Waste	α-Amylase & Amyloglucosidase (Thermamyl)	B-SHF	Saccharomyces cerevisiae	Volume 2 L Dosage 2 g/L Temp 30° C pH 5.0 Time 12 h	NR	0.25	NR	Kumar et al., 1998
Bakery Food Waste	α-Amylase, amyloglucosidace, protease and cellulase	B-SSF	Saccharomyces cerevisiae	Volume 2 L Dosage 0.13 g/L Temp 32° C pH 6.0 Time 24 h	NR	0.24	NR	Kumar et al., 1998
Waste Bread	None	B-SHF	Saccharomyces cerevisiae	Volume 0.2 L Dosage 1 g/L Temp 35° C pH 4.5 Time 72 h	NR	0.35	1.61	Pietrzak and Kawa-Rygielska, 2014
Waste Bread	α-Amylase & Amyloglucosidase (Fungamyl)	B-SHF	Saccharomyces cerevisiae	Volume 0.2 L Dosage 1 g/L Temp 35° C pH 4.5 Time 72 h	NR	0.39	1.81	Pietrzak and Kawa-Rygielska, 2014
Waste Bread	α-Amylase & Amyloglucosidase (Thermamyl)	B-SHF	Saccharomyces cerevisiae	Volume 1 L Dosage 20 g/L Temp 30° C pH 5.0 Time 10 h	100.00	0.35	NR	Ebrahimi et al., 2008
Cereal Food Waste	α-Amylase, β-Glucanase, β-Xylanase, cellulase	B-SHF	Saccharomyces cerevisiae	Volume 0.3 L Dosage 10% (v/v) Temp 30° C pH NR Time 72 h	NR	0.40	NR	Vidmantiene et al., 2006
Bakery Food Waste	None	B-SHF	Saccharomyces cerevisiae	Volume 0.3 L Dosage 2 g/L Temp 30° C pH NR Time 93 h	83.10	0.35	NR	Kawa-Rygielska et al., 2012
Wheat-Rye Bread Waste	α-amylase, β-glucanace, protease	B-SHF	Saccharomyces cerevisiae	Volume 0.3 L Dosage 2 g/L Temp 30° C pH NR Time 72 h	85.80	0.36	NR	Kawa-Rygielska et al., 2012

Table 3.3 Process parameters for the fermentation of hydrolyzed food waste feedstocks -cont'd

Type of Waste	Enzymatic Hydrolysis	Process Type	Fermentation Parameters		Concentration of EtOH (g/L)	Yield g EtOH/g TS	Production of EtOH g/l hr	Reference
			Fermentation Microorganism	Process Parameters				
Wheat-Rye Bread Waste	α-amylase, β-glucanace, protease, pentosanase, and cellulose	B-SHF	Saccharomyces cerevisiae	Volume 0.3 L Dosage 2 g/L Temp 30° C pH NR Time 72 h	88.50	0.37	NR	Kawa-Rygielska et al., 2012
Corn meal	α-Amylase & Amyloglucosidase (Thermamyl)	B-SHF	Saccharomyces cerevisiae	Volume NR Dosage 1.0 %(v/v) Temp 32° C pH 5.0 Time 48 h	78.50	0.44	1.60	Mojovic et al., 2006
Corn meal	α-amylase, and glucoamylase	B-SSF	Saccharomyces cerevisiae	Volume NR Dosage 20 g/L Temp 37° C pH 4.8 Time 60 h	82.95	NR	NR	Lei et al., 2014
Food Waste	α-amylase, and glucoamylase	B-SSF	Saccharomyces cerevisiae	[a] Volume 50 L Dosage 2 % (v/v) Temp NR pH 5.0 Time 60 h	93.79	0.47	1.56	Yan et al., 2013
Food Waste	α-amylase, and glucoamylase	B-SSF	Saccharomyces cerevisiae	[b] Volume 1000 L Dosage 20 g/L Temp NR pH 5.0 Time 54 h	96.46	0.48	1.79	Yan et al., 2013

NR Not reported,

B-SSF- Batch and Simultaneous Saccharification & Fermentation Process

B-SHF- Batch and Separate Hydrolysis & Fermentation Process

C-SSF- Continuous and Simultaneous Saccharification & Fermentation Process

C-SHF- Continuous and Separate Hydrolysis & Fermentation Process

EtOH Ethanol

[a] Semi pilot scale test

[b] Pilot scale test

Chapter 4 - Environmental Benefits

4.1 Food waste environmental impact

According to the Food and Agriculture Organization (FAO), one-third of the total global food production, about 1.3 billion tons of food, are wasted each year (Hao et al., 2015). The immense quantity of food waste emanates with environmental impact and economic cost. FAO equates food waste GHG emissions to be the third top emitter after the United States and China (Figure 4.1). Furthermore, the carbon footprint of food waste is calculated to be 3.3 Gton of carbon dioxide led by cereal food waste with 34% (Figure 4.2), without accounting the GHG emissions from land usages to produce the waste food. This wastage is costing the world economy about $936 billion each year (FAO, 2014).

Some food waste management practices have been developed and implemented to dispose of such a quantity of generated waste. Many of these practices are based on factors such as handling complexity, economic value, quantity values, or social and environmental impact consideration. Nowadays, food waste management practices include mainly: 73% animal feed, 20% landfill, 4% incineration and other processes, 2% composting, and 2% donation (Baldwin, 2015). The animal feed and composting are the most cost-effective disposal practices but sometimes are limited by regulatory and hygiene-related issues. Processing food waste also creates a large amount of wastewater when it is released, especially, when food waste is used for fertilizer. Although it is environmentally appropriate to divert effluent and solid waste from food manufacturing to reduce agriculture requirements for fertilizers and fresh water, instead of disposing of

them in landfills, the practices are still carried out at a relatively elevated cost and substantial environmental impact (Lin et al., 2013).

Energy recovery from incineration is not always feasible, due to the high content of moisture that can lead to inefficient burning or high energy cost due to evaporation for the reduction of moisture content. The anaerobic digestion process is an acceptable alternative waste management practice because it is low cost and its utilization as a renewable energy source. However, the residence time in a digester might cause delays in the disposal of food waste; Trzcinski, (2018) summarized several studies where the lowest residence time reported was 19 days.

Landfills are counterproductive. With direct and indirect emissions of methane and carbon dioxide, food waste disposed of in landfill have a high cost and a substantial environmental impact. Food waste constitutes 14.5% of municipal solid waste (EPA, 2013) which is reflected in the operation cost. On the other hand, 4.2 tons of CO_2 are emitted for every ton of food waste generated (Lin et al., 2013), in addition to other emissions into the soil, air, and water. Another example of the environmental impact is that food waste emitted 16% of US total anthropogenic methane emissions in 2010 (Ebner et al., 2014). To overcome all the disadvantages that current food waste management practices have, ethanol production from food waste has emerged as a viable substitute for the disposal of an enormous amount of food waste.

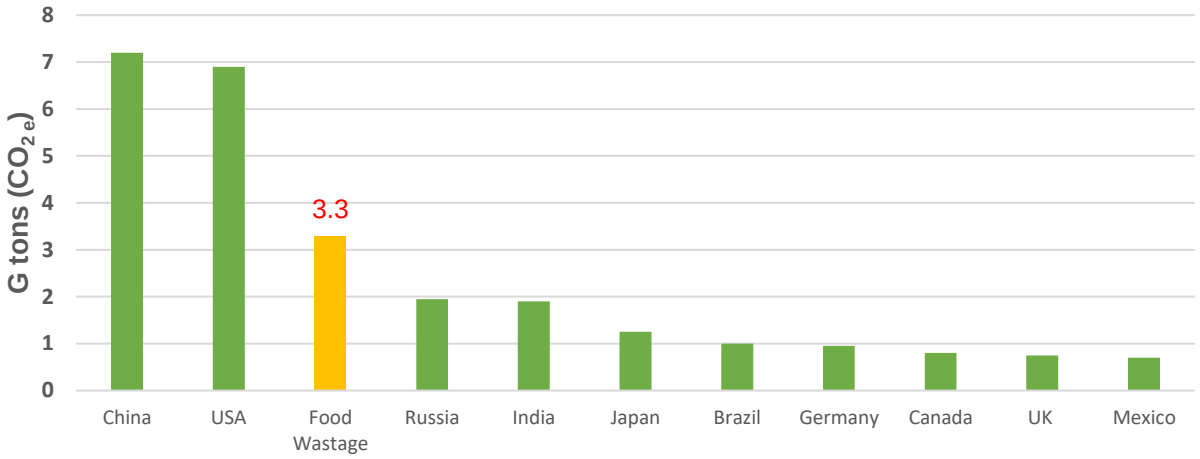

Figure 4.1 Total GHG's emissions and top 10 countries vs food wastage

Source: FAO, (2013)

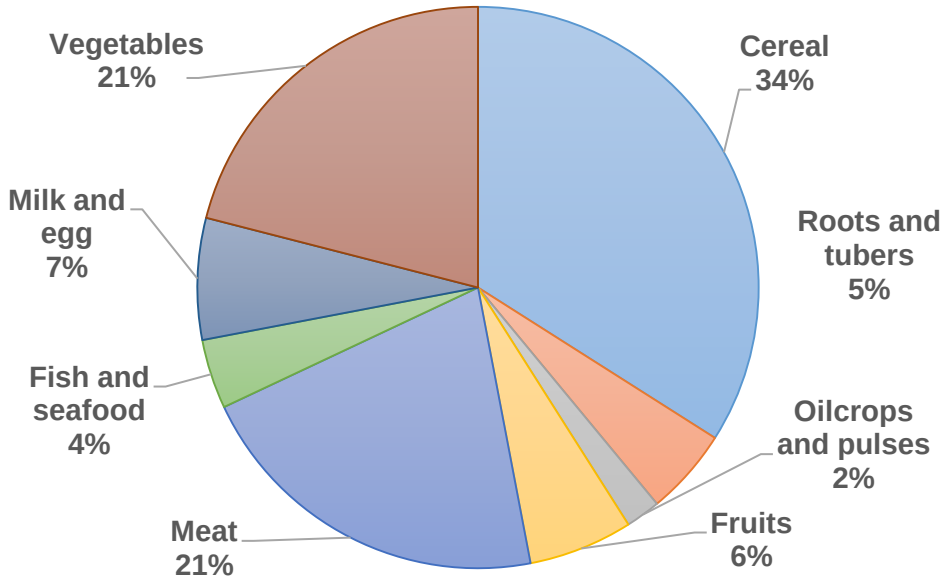

Figure 4.2 Contribution of each food commodity to food waste carbon footprint

Source: FAO, (2013)

4.2 Food waste ethanol and the environment

Renewable fuels have been considered as potential substitutes for fossil fuel, and at the same time, these fuels can mitigate the environmental impact of current transportation modes and other uses. It has been thought that the corn ethanol plant emissions are not much different from the emission generated by the production of conventional gasoline. Nevertheless, Ebner et al., (2014) estimated the life cycle for carbon dioxide emissions to produce food waste ethanol to be 1,458 g CO_2e per L EtOH, including the transportation of food waste and the wastewater treatment (Table 4.1). Additionally, if the avoided landfill emissions due to the displacement of the food waste are taken into account, the net emissions for a food waste ethanol plant are at -7132 g CO_2e per L EtOH, consequently the net ethanol process becomes carbon-negative for all scenarios when the landfill is avoided (Ebner et al., 2014).

Table 4.1 Contribution analysis of life cycle GHG impact from a food waste ethanol plant

		gCO_{2e}/ L EtOH
Electricity consumption [a]	1101	
Natural gas consumption [a]	395	
Transportation of food waste [a]	175	
Biomaterial inputs [a]	91	
Wastewater treatment [a]	9	
Net emissions food waste plant		1771
Avoided compost co-product	(54)	
Avoided animal feed co-product	(260)	
Net biorefinery emissions		1458
Displaced landfill emissions	(8590)	
Net production emissions		**(7132)**

[a] Values were combined for phase 1 and phase 2 of study.

**** Source: Ebner et al., (2014)***

Table 4.2 Summary of life cycle results for a food waste ethanol plant and a corn ethanol plant and comparison to conventional gasoline

	Food waste ethanol	Corn ethanol
Total bio-refinery emissions (gCO_{2e}/L EtOH)	1458	1608
Displaced landfill emissions	(8590)	
Net bio-refinery emissions (gCO_{2e}/L EtOH)	(7132)	1608
Net produced and distributed (gCO_{2e}/MJ) [a]	(338)	77
% Difference improvement between corn EtOH	(554)	0
% Difference improvement between conventional gasoline [b]	(460)	(17)

[a] (MJ) 1 L of ethanol converted to a unit of transport energy (1 MJ) for comparison to conventional gasoline (CG).

[b] The g CO_{2e} per MJ of conventional gasoline (CG) produced, distributed, and combusted is 94

**** Source: Ebner et al., (2014)***

In the same study, Ebner et al., (2014) also compared the emissions to corn ethanol emission and conventional gasoline. In the study analysis, it was determined that the production of ethanol by food waste feedstock has a net carbon-negative process with a 553% improvement in GHG over corn ethanol and 460% improvement over conventional gasoline (Table 4.2). The food waste ethanol is emerging, and even with its positive environmental impact, the process still has opportunities for improvements. For instance, it has been documented that the life cycle of GHG on the fermentation and hydrolysis process corresponds to 1.4-3.0% in corn ethanol production; while in other ethanol processes, it has been documented at 27-35 %, which indicates that there is still a significant gap for improvement (Trabold and Babbitt, 2018).

It is also noteworthy to specify that the fermentation process generates carbon dioxide, and it is considered biogenic in the life cycle assessment (LCA). However, to avoid the environmental impact, carbon dioxide must be captured and handled as a co-

product. By failing at capturing the generated CO_2 and releasing it into the environment causes the food waste ethanol to lose the advantage gained by avoiding food waste going into landfills.

Although the literature information about the environmental impact using food waste as a feedstock is limited, some studies show that the use of readily convertible, source-separated food waste as a feedstock to produce ethanol offers significant potential for GHG reduction and alternative options for waste-to-energy pathways.

Chapter 5 - Economic Disadvantages and Advantages

5.1 The economic disadvantages to overcome

Like any innovative process, the production of ethanol from food waste also has barriers to overcome, the availability as a feedstock is the most significant obstacle. The collection of food waste is, unquestionably, crucial, and to carry it out is a challenge. Food waste generation is mostly an interrupted and irregular process, with quality variations that affect the feedstock. Therefore, it is most likely that the raw material would possibly be coming from numerous suppliers located in a vast area. A collection network system, with routes or perhaps satellite centers, would be a necessity and would have to be implemented to supply the feedstock, consequently increasing the cost of the raw material.

Even if a biorefinery is established on the most strategic place, near bakeries, cereal food processors, or other food processing facility, it is likely that a radius of 20 to 30 miles could become insufficient to supply the necessary feedstock, and, the use of satellite centers or routes would indeed be essential to collect food waste beyond the 30 miles radius. Consequently, a routed and satellite center-based operation would raise the overall cost of food waste. It has been estimated that the average price for hauling food waste is US$ 0.20 per ton per mile (O'Connor and Manson, 2017).

The routes and satellite centers must be within one driving hour of the processing site, considering transportation regulations and the condition of the waste. Furthermore, with the opening of routes and satellite centers, it is most likely that loading and unloading

cost would be added, increasing the price for raw material. The loading and unloading cost is typically included in transportation as labor cost. This cost may well sum up 5.0 working hours for a palletized truck, timing from the truck's arrival to its departure (Burdzick et al., 2014). With an average cost of US $ 12.85 per working hour (PayScale, 2019), the average cost for loading and unloading may quickly get to US$ 3.21 per ton, hauling with a 20-ton truck.

5.2 The advantage of cereal food waste as a feedstock

One of the benefits of the process of ethanol production from food waste is the exploitation of the devaluated food that has been acknowledged as non-edible food. Moreover, Reynolds et al., (2016) estimated the essential parameters (namely total tonnage, embedded energy, and lost value on the food waste), to determine the monetary loss of the wasted bakery, sugar, and confectionery manufacturing (Table 5.1). Once the food is labeled as food waste, it has no value, and it needs to be disposed of by conventional management practices, by sending it to energy recovery processing facilities or landfills; if the latter, a tipping fee is most likely added. Currently, the national average for landfilling tip fees is US$ 50.60 / ton (Ely and Rock, 2015).

Table 5.1 Calculation of the annual loss value for waste bakery, sugar, and confectionery

Total Cost for wasted food (USD)	4,304,564
Total amount of mass waste (kg)	6,305,000
Total amount of mass waste (lbs.)	13,871,000
Total amount of energy waste (kJ)	5.32×10^{10}
Total amount of energy waste (kcal)	1.27×10^{10}
Cost per kcal (USD)	0.000339
kcal per kg	2016.67
Cost per kg (USD)	0.68
Cost per ton (USD)	682.72

**** Source: Reynolds et al., (2016), the values are based on cost in New Zealand, but the order of the value is likely to be similar across the develop world.***

The valueless food waste acquires some value when it is redirected to an energy recovery facility such as an ethanol plant, avoiding the tipping fee. However, currently, there are no parameters to define the monetary value of food waste, and there is not a price measure or trade for food waste. The Environmental Protection Agency (EPA) has an estimated value of US$ 20-65 / ton for solid organic material waste for the biogas plants overseen by the agency (Ely and Rock, 2015). Thus, assigning EPA estimated value cost and considering credit for landfill tip fee avoidance, a revenue of US$ 70.60-115.60 / ton might be designated for the food waste instead of a total loss (Table 5.2). Nowadays, the ethanol manufacturing plants are driven primarily by corn as a feedstock. Comparing the estimated cost for a food waste feedstock to that of corn reveals a 106% higher cost of corn, which gives an advantage to food waste over corn (Table 5.3).

5.3 Revenue from the co-products and the valorization of the process

Fermentation produces almost equal amounts of CO_2 and ethanol, and the ethanol industry delivers 43% of the US market. Domestic prices for CO_2 average $95 per ton, sold in a variety of containers from 105-ton rail cars to 20-pound cylinders (Mueller, 2017). For an ethanol plant to sell CO_2, a user must be nearby, and the amount of CO_2 generated must be significant enough to justify the cost of the CO_2 recovery and purification equipment.

Conventionally, the second co-product in an ethanol production process is the distiller's grains. About 6.4 pounds are produced for each gallon of fuel ethanol in a corn-based plant. In 2000, at a sales price of $0.045 per pound, the revenue of distillers' grains provided approximately 20% of the sales income to an ethanol facility (McAloon et al., 2000). Lastly, Tuck et al., (2012) demonstrated the economic advantage linked to the

valorization of waste biomass to energy recovery facilities. The average value of transportation fuels made from waste biomass was estimated to be approximately US$ 200–400 per ton of biomass. Comparatively, cattle feed ranged at US$ 70–200 per ton of waste used for feed, while electricity generation value was determined to be in the range of US$ 60–150 per ton of biomass, which highlights the significant differences in value among final products.

Table 5.2 Net losses for disposing of cereal food waste in landfill and at a food waste ethanol plant

	USD/ton	Reference
Disposing food waste at landfill		
Lost value for edible food *	(683)	Reynolds et al., 2016
Landfill Tip Fee	(51)	Ely & Rock, 2015
Net loss for wasted food	**(734)**	
Disposing at food waste ethanol		
Lost value for edible food *	(683)	Reynolds et al., 2016
Solid Organic waste value	60	Ely & Rock, 2015
Credit for avoiding landfill	51	Ely & Rock, 2015
Net loss for wasted food	**(572)**	

Value based on waste tonnage, disposal cost and monetary losses of bakery, sugar, and confectionery manufacturing waste in New Zealand

Table 5.3 Solid organic waste feedstock value per ton and comparison to corn feedstock price

	USD/ton	Reference
Solid organic waste value	60	Ely & Rock, 2015
Loading and unloading *	3	Ely & Rock, 2015
Hauling fee (30 miles trip)**	6	O'Connor & Manson, 2017
Net cost for solid organic waste	69	
Solid organic material feedstock	69	
Corn feedstock price	142	Indexmundi, 2019
Percent difference	106%	

**** Based on five working hours to load and unload***
**** *Based on the estimate of $4/20 ton.***

5.4 Potential ethanol from cereal food waste and crop residues

For decades, corn ethanol production has brought a dilemma that has been the subject of debate today. The food vs. fuel dilemma has generated studies where the promoters of ethanol have supported and demonstrated that the use of crops in ethanol production impacts neither the supply nor the price of the crops. Although in 2016, 38% of corn production in the United States was used for ethanol production (Trabold and Babbitt, 2018), there was no proven impact on the corn price during that year or the subsequent years as shown on Figure. 5.1. Correspondingly, Figure. 1.1 demonstrates how different factors drive the cereals' costs, such as economic behavior. For example, as shown in Figure 1.1, all cereal commodities were traded at higher prices as a response to the Great Recession of 2008. Nevertheless, it is the corn production, utilized for ethanol biorefineries, that makes the most notable impact by raising different environmental concerns such as soil erosion, pollutants from the use of fertilizers, the use of excess irrigation water, among others.

Because cereals are the most produced food and topped the list in contribution to food waste carbon footprint with a total of 34% (Baldwin, 2015), cereal food waste is now being considered as a potential suitable replacement to reduce the corn usage and other crops in the ethanol production and end the food vs. fuel dilemma.

Cereal waste and cereal crop residues constitute large quantities of biomass that can potentially be used for ethanol production. It is estimated that there is a total of 70.1 Tg of cereal waste, and it could produce 47.5 GL of ethanol per year. Similarly, an ethanol production of 390.7 GL per year is estimated from a total of 1,369 Tg of cereal crop residues (Table 5.4). However, lignocellulosic feedstock requires a tremendous effort to achieve a cost-effective ethanol yield, and several factors affect this yield, such as an

infrastructure system for the collection of waste, an increase in thermal efficiency to generate electricity and steam, among others (Kim and Dale, 2004). Nevertheless, if the ethanol production from cereal biomass is optimized and made cost-effective, about 438.2 GL of ethanol could possibly be produced from cereal waste and cereal crop residues (Table 5.4), approximately four times higher than the 107.9 GL produced world worldwide in 2018 (RFA, 2019). In North America, the ethanol to be produced potentially from cereal waste and cereal crop residues is approximately 62.7 GL (Table 5.4) compared to the actual 2018 ethanol production of 62.61 G/L (RFA, 2019). Biomass availability from cereal food waste is a viable substitute and reliever for crops, mitigating the environmental impact, unaffecting the food supply chain, and closing the food vs. fuel dilemma.

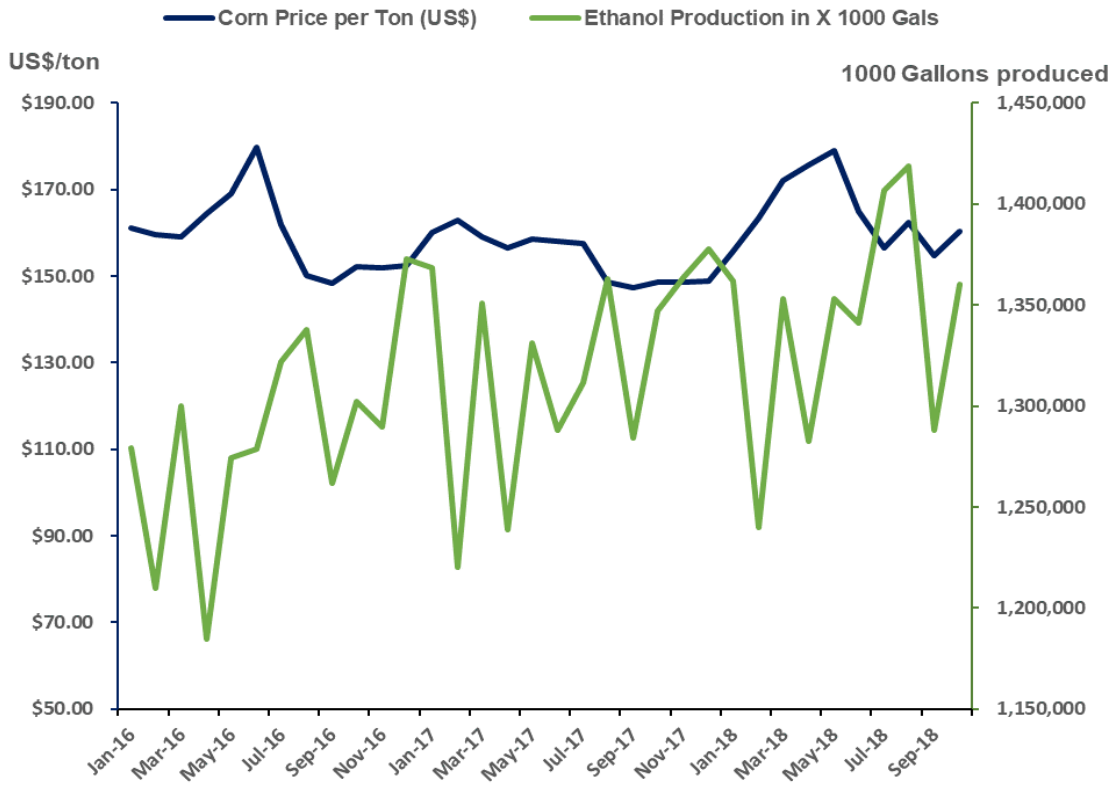

Figure 5.1 Corn price vs. ethanol production (2016-2018)

Source: Ethanol production RFA, (2019), Corn price Indexmundi, (2019)

Table 5.4 Quantities of cereal waste potentially available for ethanol production

	Quantities from wasted cereal (Tg)	Quantities from cereal crop residues (Tg)	Potential ethanol from Cereal waste (GL)	Potential ethanol from cereal crop residues (GL)	Total ethanol (GL)
World cereal waste and the potential for ethanol production					
Corn	20.70	203.62	14.38	58.60	72.98
Barley	3.66	58.45	2.46	18.10	20.56
Oats	0.55	10.62	0.39	2.78	3.17
Rice	25.44	731.34	16.80	204.60	221.40
Wheat	17.20	354.35	11.33	103.80	115.13
Sorghum	3.12	10.32	2.14	2.79	4.93
Totals	70.67	1368.70	47.50	390.67	438.17
North America cereal waste and the potential for ethanol production					
Corn	0.30	133.66	0.21	38.40	38.61
Barley	0.01	9.85	0.01	3.06	3.07
Oats	0.01	2.80	0.01	0.73	0.74
Rice	0.96	10.95	0.63	3.06	3.69
Wheat	0.02	50.05	0.02	14.70	14.72
Sorghum	0.00	6.97		1.89	1.89
Totals	1.30	214.28	0.87	61.84	62.72

**** Source: Kim and Dale, (2004)***

Chapter 6 - Conclusion

6.1 The problems of food waste, ethanol production, and the solution

Despite all efforts to eliminate food waste, the potential of embedded energy is still underestimated. Cuellar and Webber (2010) estimated a total of 2030 trillion BTUs incrusted in food waste, of which 271 trillion BTUs are in the cereals' waste. Food is not only a source of energy but also consumes energy; therefore, with the loss of food, not only energy embedded is lost, but along with it all the energy for its production, preparation, and transportation. According to FAO (2011), one-third of the food is wasted, and with it, valuable agricultural resources are lost such as soil, water, and labor, and unnecessary issues arise with the production of that one-third of the food that is lost in the entire food supply chain. Some of the problems that the agricultural system encounters are the land use conflict, the excess of fertilizers, deforestation, among others. Moreover, food waste needs to be disposed of, and when landfilling practices generate GHG emissions that could be avoided if the food was consumed.

On the other hand, there is the ethanol industry; currently, 95% of US ethanol production comes from the fresh crops, which demand soil, water, and other agriculture needs. Also, with the use of crops comes the dilemma of food versus fuels, where the problems generated by farming, the supply chain and even the price of the crops are debated.

By means of cereal food waste as a feedstock, food waste presents an alternative solution to avoid the problems caused by using crops for ethanol production, whereas it addresses the waste management challenge due to the high volume of food waste. The potential for ethanol production from waste cereal and cereal crops residues is a viable

alternative, and the manipulation of these wastes as a feedstock, instead of landfilling them, must be recognized as a sustainable objective. Biorefineries, however, must be cost-effective, and the food waste ethanol should be competitive on the market, making the economic factors play an essential role; therefore, integration of food waste ethanol with corn ethanol or sugar ethanol might need minor investment since most of the unit operations are shared by both processes. Starting with cereal, food waste is an attractive and suitable raw material for ethanol production that can follow a sustainable green route with a minimum environmental impact.

References

Adessi, A., Venturi, M., Candeliere, F., Galli, V., Granchi, L., & De Philippis, R. (2018) Bread wastes to energy: Sequential lactic and photo-fermentation for hydrogen production. International Journal of Hydrogen Energy. 43. 20.9569-9576.

Baldwin C.J. (2015). Food Industry Sustainability. John Wiley & Sons. First Edition. 2015. West Sussex, UK.

Bothast, R.J. & Schlicher, M. (2005). Biotechnological processes for conversion of corn into ethanol. Appl Microbiol Biotechnol. 67. 1. 19-25.

Burdzik, R., Cieśla, M., & Sładkowski, A. (2014). Cargo Loading and Unloading Efficiency Analysis in Multimodal Transport. PROMET - Traffic&Transportation. 26. 4. 323-331.

Cardona, C.A., Sánchez, O.J., Montoya, M.I., & Quintero J.A. (2005). Simulación de los procesos de obtención de etanol a partir de caña de azúcar y maíz. Scientia et Technica. XI. 28. 187-192.

Chen, W.C., Sheng, C.T., Liu, Y.C., Chen, W.J., Huang, W.L., Chang, S.H., & Chang, W.C. (2014). Optimizing the efficiency of anhydrous ethanol purification via regenerable molecular sieve. Applied Energy. 135. 483-489.

Cuellar, A. & Webber, M. (2010). Wasted Food, Wasted Energy: The Embedded Energy in Food Waste in the United States. Environ.Sci.Technol. 44. 16. 6464-6469.

Dewettinck, K., Van Bockstaele, F., Kühne, B., Walle, D., Courtens, T.M. & Gellynck, X. (2008). Nutritional value of bread: Influence of processing, food interaction and consumer perception. Journal of Cereal Science. 48. 2. 243-257.

Ebner, J., Babbitt, C., Winer, M., Hilton, B., & Williamson, A. (2014). Life cycle greenhouse gas (GHG) impacts of a novel process for converting food waste to ethanol and co-products. Applied Energy. 130. 86–93.

Ebrahimi, F., Khanahmadi, M., Roodpeyma, S., & Taherzadeh, M. (2008). Ethanol production from bread residues. Biomass and Bioenergy. 32. 4. 333-337.

ElMekawy, A., Diels, L., De Wever, H., & Pant, D. (2013). Valorization of Cereal-Based Biorefinery Byproducts: Reality and Expectations. Environmental science & technology. 47. 16. 9014-9027.

Ely, C. & Rock, S. (2015) Food Waste to Energy: How Six Water Resource Recovery Facilities are Boosting Biogas Production and the Bottom Line. U.S. Environmental Protection Agency. Washington, DC. EPA/600/R-14/240, 2015.

EPA. (2013) Municipal Solid Waste in the United States 2011 Facts and Figures. US Environmental Protection Agency. Office of Solid Waste Washington, DC. (5306P) EPA530-R-13-001. www.epa.gov. May 2013.

EPM, Ethanol Producer Magazine. (2019). Operational U.S. Ethanol Plants. http://www.ethanolproducer.com/plants/listplants/US/Operational/All. /. Accessed March 18, 2019.

FAO. (2011). Global food losses and food waste – Extent, causes, and prevention. Food and Agricultural Organization of the United Nations. Rome, Italy.

FAO. (2013) Food wastage footprint, Impacts on natural resources. Summary Report. Food and Agricultural Organization of the United Nations.adia.Scialabba@fao.org.

FAO. (2014). Food Wastage Footprint. Full Cost Accounting. Final Report. Food and Agricultural Organization of the United Nations. Rome, Italy.

FAO. (2019). FAOSTAT. http://www.fao.org/faostat/en/#data/QC. Food and Agricultural Organization of the United Nations. Rome, Italy. 2019. Accessed March 22, 2019.

Fung, L., Urriola, P.E., Baker, L., & Shurson, G.C. (2018). Estimated energy and nutrient composition of different sources of food waste and their potential for use in sustainable swine feeding programs. Translational Animal Science. 3. 1.

Han, W., Liu, WX., Yu, C., Huang, JG., Tang, JH., & Li, YF. (2017). BioH_2 production from waste bread using a two-stage process of enzymatic hydrolysis and dark fermentation. International Journal of Hydrogen Energy. 42. 50. 29929-29934.

Hao, H-T. N., Karthikeyan, O.P., & Heimann, K. (2015). Bio-Refining of Carbohydrate-Rich Food Waste for Biofuels. Energies. 8. 7. 6350-6364.

Indexmundi. “Commodity Agricultural Raw Materials Index,” www.indexmundi.com/ commodities/?commodity=agricultural-raw-materials-price-index. Accessed March 14, 2019.

Kawa-Rygielskaa, J., Pietrzak, W., & Czubaszek, A. (2012) Characterization of fermentation of waste wheat-rye bread mashes with the addition of complex enzymatic preparations. Biomass and Bioenergy. 44. 17-22.

Kim, J.H., Lee, J.C., & Pak, D. (2011). Feasibility of producing ethanol from food waste. Waste Management. 31. 9. 2121-2125.

Kim, S. & Dale, B. (2004). Global Potential bioethanol Production from Wasted Crops and Crop Residues. Biomass and Bioenergy. 26. 4. 361-375.

Kiran E.U., & Liu, Y. (2015). Bioethanol production from mixed food waste by an effective enzymatic pretreatment. Fuel. 159. 463-469.

Kumar, JV., Mathew, R., & Shahbazi A. (1998). Bioconversion of solid food wastes to ethanol. Analyst. 3. 497-502.

Lei, C., Zhang, J., Xiao, L., & Bao, J. (2014). An alternative feedstock of corn meal for industrial fuel ethanol production: Delignified corncob residue. Bioresource Technology. 167. 555-559.

Leung, C.C.J., Cheung, A.S.Y., Zhang, A.Y., Lam, K.L., & Lin, C.S.K. (2012). Utilisation of waste bread for fermentative succinic acid production. Biochemical Engineering Journal. 65. 10-15.

Levis, J.W., & Barlaz, M.A. (2011). What Is the Most Environmentally Beneficial Way to Treat Commercial Food Waste? Environ.Sci.Technol. 45. 17. 7438-7444.

Lin, C. S. K., Pfaltzgraff, L. A., Herrero-Davila, L., Mubofu, E. B., Solhy, A., Clark, J. H., & Luque, R. (2013). Food waste as a valuable resource for the production of chemicals, materials, and fuels. Current situation and global perspective. Energy and Environmental Science, 6.2. 426-464.

Manikandan, K & Viruthagiri, T. (2010). Kinetic and Optimization Studies on Ethanol Production from Corn Flour. International Journal of Chemical and Biological Engineering. 3. 2. 65-69.

Matsakas, L. & Christakopoulos, P. (2015). Ethanol Production from Enzymatically Treated Dried Food Waste Using Enzymes Produced On-Site. Sustainability. 7. 2. 1446-1458.

McAloon, A., Taylor, F., Yee, W., Ibsen, K., & Wooley, R. (2000). Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks. United States.

McDonald, A.G., Boyce, S., & Tipton, K.F (2009). ExplorEnz: the primary source of the IUBMB enzyme list. Nucleic Acids Res. 37, D593–D597. www.enzyme-database.org. 2009. Accessed Mar 25, 2019.

Meenakshi, A & Kumaresan, R. (2014). Ethanol production from corn, potato peel waste, and its process development. International Journal of ChemTech Research. 6. 5. 2843-2853.

Melikoglu, M. & Webb, C. (2013). Use of Waste Bread to Produce Fermentation Products. Food Industries Wastes. Elsevier Publication. Chapter 4. First Edition. 63-76.

Merrill, Annabel L & Watt, Bernice K. (1955) Energy Value of Foods: basis and derivation. Human Nutrition Research Branch, Agricultural Research Service, U.S. Dept. of Agriculture, Washington, D.C.

Mojović, L., Nikolić, S., Rakin, M., & Vukasinović, M. (2006). Production of bioethanol from corn meal hydrolyzates. Fuel. 85 1750-1755.

Mueller, S. (2017). Ethanol industry provides critical CO2 supply. Ethanol Producer Magazine. March 2017. 48-49.

Mumm, R. H., Goldsmith, P. D., Rausch, K. D., & Stein, H. H. (2014). Land usage attributed to corn ethanol production in the United States: sensitivity to technological advances in corn grain yield, ethanol conversion, and co-product utilization. Biotechnology for biofuels. 7. 61. 1-17.

Mustafa, A.F., McKinnon, J.J. & Christensen, D. (2000). Chemical characterization and in situ nutrient degradability of wet distillers' grains derived from barley-based ethanol production. Animal Feed Science and Technology. 83. 3-4. 301-311.

Naidu, K.S., Johnston, V., Kent, D.R., & Tumbleson, M. (2007). Effects of Ground Corn Particle Size on Ethanol Yield and Thin Stillage Soluble Solids. Cereal Chemistry Journal. 84. 1. 6-9.

NREL Biofuel Atlas. (2019). National Renewable Energy Laboratory. maps.nrel.gov/biofuels-atlas/ Accessed March 18, 2019.

O'Connor, K. & Manson C. (2017). Benefit-Cost Analysis of Potential Food Waste. Diversion Legislation. New York State Energy Research and Development Authority. nyserda.ny.gov. Albany, NY.

Paritosh, K., Kushwaha, S.K., Yadav, M., Pareek, N., Chawade, A., & Vivekanand, V. (2017). Food Waste to Energy: An Overview of Sustainable Approaches for Food Waste Management and Nutrient Recycling. BioMed Research International. (2017). ID 2370927.1- 19.

PayScale. (2019). Average Warehouse Worker Hourly Pay. www.payscale.com. Accessed on April 8, 2019.

Pietrzak, W., & Kawa-Rygielska, J. (2014). Ethanol fermentation of waste bread using granular starch hydrolyzing enzyme: Effect of raw material pretreatment. Fuel. 134. 250-256.

Probstein, R.F. & Hicks, R.E. (1982). Synthetic Fuels. McGraw Hill Inc. First Edition. New York, NY.

RFA. (2019). Market and Statistics. Renewable Fuels Association. www. ethanolrfa.org/ resources/industry/statistics/. Accessed March 18, 2019.

Reynolds, C.J.; Mirosa, M.; & Clothier, B. (2016). New Zealand's Food Waste: Estimating the Tonnes, Value, Calories, and Resources Wasted. Agriculture. 6. 9.

Samson, R.A., Hoekstra, E.S., & Frisvad, J.C. (2004) Introduction to Food and Airborne Fungi. CBS Printing. Seventh Edition. Ultrecht, The Netherlands.

Tanimu, M.I., Ghazi, T., Harum, R.M., & Idris, A. (2014). Effect of Carbon to Nitrogen Ratio of Food Waste on Biogas Methane Production in a Batch Mesophilic Anaerobic Digester. International Journal of Innovation, Management, and Technology. 5. 2. 116-119.

Trabold, T.A., & Babbitt, C.W. (2018). Sustainable Food Waste-To-Energy Systems. Academic Press. First Edition. London, UK.

Trzcinski, A.P. (2018). Biofuel from Food Waste, Application of Saccharification Using Solid State Fermentation. CRC Press. First Edition. Boca Raton FL.

Tuck, C. O., Pérez, E., Horváth, I., Sheldon, R. A., & Poliakoff, M. (2012). Valorization of biomass: Deriving more value from waste. Science. 337.6095. 695-699.

Tyner, W.E. (2013). Biofuels and food prices: Separating wheat from chaff. Global Food Security. 2. 2. 126-130.

Vidmantiene, D., Juodeikiene, G., & Basinskiene, L. (2006). Technical ethanol production from waste of cereals and its products using a complex enzyme preparation. J Sci Food. Agric. 86. 11. 1732-1736.

Yan, S., Chen, X., Wu, J. & Wang, P. (2013) Pilot-scale production of fuel ethanol from concentrated food waste hydrolysates using Saccharomyces cerevisiae H058. Biosyst Eng. 36. 7. 937-946.

Appendix A - Acronyms

C/N	Carbon-Nitrogen Ratio
CO_2	Carbon Dioxide
DDG	Dried Distillers Grain
EPA	Environmental Protection Agency
EPM	Ethanol Producer Magazine
EtOH	Ethanol
FAN	Free Amino Nitrogen
FAO	United Nations Food and Agriculture Organization
GHG	Greenhouse Gases
LCA	Life Cycle Assessment
NREL	National Renewable Energy Laboratory
RFA	Renewable Fuel Association
SHF	Separate Hydrolysis and Fermentation Process
SSF	Simultaneous Saccharification and Fermentation Process
US	United States of America
USDA	United States Department of Agriculture
WDG	Wet Distillers Grain