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A Quantitative Environmental Assessment of Incorporating Torrefaction into Farming Enterprises in Eastern South Dakota

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A QUANTITATIVE ENVIRONMENTAL ASSESSMENT OF INCORPORATING TORREFACTION INTO FARMING ENTERPRISES IN EASTERN SOUTH DAKOTA

BY

DINESH FUYAL

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Mechanical Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	**Explanation**
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ISO	International Organization for Standardization
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
EP	Eutrophication Potential
AP	Acidification Potential
N	Nitrogen
N_2O	Nitrous oxide
NO_x	Oxides of nitrogen
NO_3^-	Nitrate
GHGs	Greenhouse gases
SOC	Soil organic carbon
CO_2	Carbon dioxide
CO	Carbon monoxide
SD	South Dakota

GaBi	Ganzheitlichen Bilanzierung (German means Holistic Balance)
GLO	Global
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
CML	Centre of Environmental Science
EPA	Environmental Protection Agency
ECN	Energy Research Centre of the Netherlands
ILCD	International Reference Life Cycle Data System
NPK	Nitrogen, Phosphorous, Potassium

UNITS OF MEASURE

kg	kilogram
gal	gallon
kJ	kilojoule
MJ	megajoule
kW	kilowatt
kWh	kilowatt hour
t	metric ton
TWh	Terawatt-hour (10^{12} watt-hours)
BTU	British thermal unit
m^3	cubic meter
km	kilometer
kgkm	kilogram-kilometer
$	United States dollar
kg equivalent of CO_2	unit to measure global warming potential
kg H+ moles equivalent	unit to measure acidification potential
kg N equivalent	unit to measure eutrophication potential

acre	a unit of land area used in the imperial and US customary systems (approx.4,047 square meters)
hectare	a unit of land area primarily used in the measurement of land as a metric replacement for the imperial acre (10,000 square meters)
bushel	imperial and US customary unit of weight or mass (56 lb for corn and 60 lb for wheat and soybean)

ABSTRACT

A QUANTITATIVE ENVIRONMENTAL ASSESSMENT OF INCORPORATING TORREFACTION INTO FARMING ENTERPRISES IN EASTERN SOUTH DAKOTA

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The use of renewable energy sources has been increasing in the recent years due to population growth and environmental concerns. Biomass is a promising energy source that can be used to produce biofuels or torrefied pellets. Torrefied biomass may be used in power plants, industrial and residential heating, feedstocks for gasification, air and water filtrating, and soil amendment. The interest of torrefied pellets as energy sources for various applications has been increased in the recent years due to the concerns about energy security and environmental issues. This study focuses on the economic and environmental assessment of agricultural feedstocks like corn stover, wheat straw, and soybean residues capable of producing torrefied pellets in the Eastern & Central South Dakota, Brookings. The techno-economic and environmental analysis of these feedstocks is required to understand the supply chain. GaBi ts – Life Cycle Assessment software, version 6.115 was used to analyze the potential environmental impacts of crop residues from the viewpoint of farmers and torrefaction facility. This study recommends farmers to follow corn-soybean rotation to have both the economic and environmental benefits. This study also shows that, when done responsibly, residue-based torrefaction reduce dependence on coal. Also, one of the significant findings from this LCA study is that crop residues are beneficial to crop grains in terms of global warming potential but have higher environmental emissions in terms of acidification and eutrophication potential.

Chapter 1 INTRODUCTION

The primary focus of this chapter is to provide the benefits of renewable energy sources, especially biomass in terms of economic and environmental perspectives. Biomass can produce various energy products such as bioethanol, biodiesel, bio-oil and torrefied pellets. These energy products can be used as a fuel for automobile or cofiring with coal in power plants, which reduces the dependency on non-renewable energy sources (coal, petroleum, and natural gas).

1.1 Problem Statement

With regard to increasing population and reduction in the availability of non-renewable energy sources (like coal), biomass, a locally available renewable source, has a good scope to fulfill the energy demand. Renewable energy accounted for 10% of total primary energy consumption and 15% of electricity generation here in the United States in 2016 [1]. Renewable energy sources are gaining attention due to the uncertainty of non-renewable energy sources. For example, corn-derived ethanol accounts for about 10% of U.S. gasoline consumption. Biomass currently provides 2% of America's electricity and 1% of the fuel used in cars and trucks [2]. In addition to the many benefits common to any renewable energy use, biomass is particularly attractive since these energy resources could be used as a renewable source of liquid transportation fuel. This helps to reduce the oil imports in the US. Biomass also has a huge potential to provide heat and power to industry and serves as a feedstock to make a wide range of chemicals and materials or bioproducts [3].

Agricultural residue has a significant potential for energy production processes, however, most of them remain untapped. The agricultural residues like corn stover, wheat straw, and soybean residues can be used to produce bio-based energy products i.e. torrefied pellets, bio-ethanol, biodiesel, etc. The market for such renewable energy resources has been growing in the last decade due to people's concerns about clean energy and public policy to reduce the carbon dioxide emissions. Coal combustion is recognized as the main source of the anthropogenic carbon emission. Biomass being carbon neutral could replace coal in existing power plants to provide energy while reducing carbon emissions at affordable cost [4]. Therefore, to meet the increasing demand on energy, we need to focus on the sustainable energy practices by reducing the use of fossil fuels.

1.2 Life Cycle Assessment

Life Cycle Assessment (LCA), as defined by the ISO standards, is the compiling and evaluation of the inputs and outputs and the potential environmental impacts of a product system during its lifetime [5]. The ISO 14040 standard introduces LCA and has applicable definitions and background information, while the ISO 14044 describes the process of conducting an LCA [6]. LCA is a study about the potential environmental impacts throughout a product's life cycle starting from the raw materials to the production of products or the final delivery of waste. In other words, life cycle assessment is the process of analyzing the potential environmental impacts of a product, service, or a system, which helps to identify the hotspots and focuses on the sustainability. LCA is fast becoming a useful tool for product designers and production managers. Until now, LCA has been mostly used by experts because of the complex nature of the analysis [7]. LCA can be used for quite different purposes: for bottleneck identification and product innovation in industry, for marketing and information of consumers, for strategic planning within companies and for policy planning [8]. Thus, LCA gives an answer of how a certain product can be produced with minimum environmental impact.

This study uses LCA to evaluate the environmental emissions and energy use of these agricultural residues, which have the potential to produce torrefied pellets. This study intends to look at the life cycle assessment of crop production and torrefaction process from the farmers and torrefaction facility perspective. The market for torrefied biomass is promising due to the focus on cleaner energy. Torrefied pellets has thus a potential for alternative fuel source which are produced mostly from the woody biomass or crop residues. According to Shen et al., the inputs and boundaries of LCA vary with different feedstocks, such as forestry wood, agricultural residues, and fast-growing grass. The GHG emissions also vary with different feedstocks and depend on burning technologies at different plant scales [9].

Some of the few considerations that the business companies can consider while performing LCA-activities are summarized below as:

- Amongst the several instruments used for an environmental assessment of products and services, the company should choose the tool that offer the most opportunity for them.
- LCA is a prominent tool, but very likely it has to be streamlined to the respective purposes.
- The environmental situation is always complex. So, LCA confronts you with a consideration of the life cycle impacts of your products across environmental media.

- LCA contributes to a better understanding of environmental complexity; it designs situations, but it does not solve them.
- LCA might play different roles among the product development chain [8].

However, LCA studies has few limitations which are given below:

- LCA does not typically address the economic and social aspects of a product.
- The nature of choices and assumptions made in LCA may be subjective.
- Models are limited by their assumptions and may not be available for all potential impacts/applications.
- The accuracy of LCA studies may be limited by accessibility or availability of relevant data, or data quality [10].

1.2.1 Agricultural Life Cycle Assessment

Field residues are the biomass left in the field after the harvest. These residues can be utilized as an energy carrier product. The crop residues that are considered for this study are corn stover, wheat straw, and soybean residues. This study focuses on the life cycle assessment (LCA) of the torrefaction process using these agricultural residues. The study of LCA of crop production includes all the phases from the soil preparation to the harvest. After the harvest of the corresponding crops, we have the residues left in the field, which can be sustainably removed at an appropriate percentage. Studies concluded that about one-third to one half of corn stover in cornfields can be sustainably removed without causing erosion or deteriorating soil quality [11]. Therefore, agricultural LCA focuses on the dynamics of sustainable agriculture. Sinha (2009) defined sustainable agriculture as the “successful management of resources for agriculture to satisfy the changing human requirements whilst maintaining or enhancing the quality of environment and conserving natural resources". This practice of sustainable agriculture integrates three main goals: environmental health, economic profitability, and social equity [12].

Agricultural life cycle assessments (LCAs) are becoming increasingly important with the growth of biofuels such as biodiesel, ethanol, and bio-based products like biopolymers that have been driven by U.S. policies to reduce the dependency on fossil fuel [13]. Apart, agricultural practices and yields are closely linked to climate and soil conditions, cropping intensity, input prices and cultural habits, all parameters that are highly variable and dependent on regional specificities [14].

Corn production emits greenhouse gases emissions from upstream operations like fertilizer production and crop chemicals production. The N in corn stover and in fertilizer emits N_2O. Nitrogen, phosphorus, and potassium nutrients are removed with the harvest of corn stover, but we can assume the nutrient lost from corn stover removal can be balanced later with the use of fertilizers. In addition to this, when land is used to produce biofuel feedstock, a direct impact includes changes in below ground and above ground carbon content. These land use change cause soil organic carbon (SOC) content to either decrease or increase, depending on the identity of the crop. For example, if the land is converted from cropland-pasture to cornfield, SOC will decrease and carbon will be released into the atmosphere [15].

1.2.2 GaBi LCA Software

GaBi is derived from the German word ***Ga****nzeheitliche* ***Bi****lanz*, which means 'holistic balance'. Developed by PE International, a sustainability software and consulting company in Stuttgart, Germany, GaBi ts is the established standard software for the study of Life Cycle Assessment (LCA). GaBi software has its own databases and external databases e.g. Ecoinvent, USLCI, etc. This software calculates results using sequential modeling. GaBi also includes an i-report feature to produce reports with results. GaBi provides the tools to manage large datasets, model product life cycle systems, calculate energy and mass balances and interpret the results of the life cycle balances [16].

GaBi evaluates the environmental impacts of a product system based on a plan. The plan consists of various relevant processes and flows. Flows represent the inputs and outputs associated with the processes. Flows are denoted by means of mass, energy, and costs with their numeric value. Flow contain the information that tells GaBi to what extent one unit of this flow contribute to different environmental impact categories: these are called classification and characterization factors.

1.3 Torrefaction

Torrefaction, also known as mild or slow pyrolysis, is a thermo-chemical process in an oxygen-deprived environment used to enhance the quality of biomass. The word torrefaction originates from the French word ***torréfaction***, typically of coffee beans where the air is heated at low temperatures [17]. This process reduces the mass of wood by 20-30% resulting in a denser higher-valued product which can be transported more economically than the traditional wooden chips [18].

Torrefaction can simply be defined as a slow pyrolysis of lignocellulosic biomass at a temperature range of 250-300°C for 10-30 minutes in an inert environment. Torrefaction technology has been gaining its popularity in the biomass industry as it provides a robust product, produces lower greenhouse gas emissions and could be flexible with the feedstocks. It removes moisture and low weight volatile components and depolymerizes the long polysaccharide chains, which produces a hydrophobic solid product and an increased energy density and grindability [19].

When the organic biomass is subjected to higher temperatures, the moisture content will be driven off (approximately above 200°C) making this hydrophobic and thermal decomposition take place thereby changing the physical and chemical properties. On the other hand, volatiles will remain in the biomass when efficient torrefaction is done. Thus, torrefaction starts with moisture evaporation, followed by partial devolatilization. Part of the biomass volatilizes forming a torrefaction gas, that can be used for combustion and the heat is used for biomass drying and heating of the torrefaction process [20]. Volatiles include condensable like acetic acid, methanol, furfural, and water, and permanent gases like carbon dioxide, carbon monoxide, methane, hydrogen, etc. [21].

Torrefaction is generally done with woody biomass, but we can also use agri-residues like corn stover, wheat straw, rice husk, bagasse, sawdust, peanut husk, etc. According to Uslu et al., the use of untreated biomass creates problems due to its susceptibility to microbial degradation, heterogeneous composition and high bulk volume which complicate process control and logistics management [22]. There are several key questions concerned with the torrefaction industry like which biomass is sustainable, which biomass yields higher heating value, etc. Also, there are few challenges regarding the local and governmental policy. The benefits of torrefaction are its:

- Increased energy density and energy performance (calorific value);
- Improved combustion performance;

- Viability as a co-fire fuel to burn with coal;
- Reduced transportation cost of biomass per BTU, as it is done near the point of harvesting;
- Ability to produce high-grade solid biofuels from woody biomass or agro-residues;
- Capability in forming superior briquettes and pellets;
- Decreased sensitivity to degradation due to hydrophobic nature;
- Increased grindability for efficient co-firing (reduced fibrous and tenacious nature of biomass);
- Improved product quality with higher efficiency;
- Production of torrefied powder that meets the smooth fluidization regime for feeding (gasifier and pulverized coal boiler);
- Superior handling, milling, and co-firing capabilities compared to other biofuels.

Due to numerous benefits of the torrefaction process, different organizations, mainly from Europe and North American regions are extensively working on research and development of commercial torrefaction units and checking the technical and economic viability of overall systems [4]. The torrefaction process is rapidly gaining popularity because it reduces the volume of the biomass along with a reduction in moisture and chlorine, which significantly improves the grinding properties [23]. Torrefaction can be incorporated in a bio-renewables production chain to significantly reduce the cost of biomass feedstock storage, transportation, and downstream processing through the enhancement of biomass hydrophobicity, resistance to microbial degradation, energy density, homogeneity, brittleness, and chemical characteristics important for thermochemical downstream processing [24].

1.4 Carbon footprint and Global Warming Potential

Carbon trust, an industry focused on carbon management and reduction, defines carbon footprint as the total set of greenhouse gas emissions caused directly and indirectly by an [individual, event, organization, product] expressed as CO2e [25]. When one product with a lower C footprint replaces another with a larger C footprint, and thus the larger C footprint is not used, then an avoided C input to the atmosphere is claimed, this is called a negative C footprint contribution: termed displacement. For example, when torrefied pellets are used as an energy source in power generation applications as a replacement of coal, then the net carbon footprint is the difference of the C footprint effect from torrefied pellets and coal which is claimed to be negative.

Global Warming Potential (GWP) is a relative measure of how much heat a greenhouse gas can trap within the atmosphere. They are measured over a lifespan of 20, 100 or 500 years. GWP is measured relative to carbon dioxide whose GWP is one [26]. Intergovernmental Panel on Climate Change has defined GWP as an index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO_2) [27].

1.5 Socio-Economic Impacts

Biomass energy has the potential to supply a significant portion of America's energy needs, revitalize rural economies, increase energy independence and reduce pollution. If we can build a new torrefaction process in the surrounding locality of a community, it helps to create employment opportunities for the local people with their skill development. Also, the farmers can have an additional source of revenue by selling the agricultural residues to the torrefaction facility. In addition, switching to torrefaction plant will have more environmental benefits than using the coal-fired power plant. So, the crop residues based torrefaction facility has the potential to provide substantial economic benefits to the local economy.

The socio-economic aspects of a locally established torrefaction plant from the viewpoint of various stakeholders are shown below in tabular form.

Table 1-1 Socio-Economic benefits of Torrefaction Facility

Farmer	**Torrefaction Facility**	**Community**
• Effective harvesting and managed logistics • Productivity • Profit-oriented • Reduced soil erosion • Increased Biodiversity • Focus on Green Innovation • Protect the environment • Food security • Household Income	• Clean Energy Business • Production of torrefied pellets emphasizes green technology • Energy Efficient process • Creation of local jobs • Energy Security • Protection of environment by focusing on renewable energy usage • Effective use of field residues	• Air quality issues & regulations • Reduced deforestation • Food security • Household Income

1.6 Economic Analysis of Crop Production

The economic study of three major agricultural crops namely corn, wheat, and soybean discuss the inputs and outputs that are associated with the crop production. The inputs can be figured out as the expenses, which may be the direct expenses, fixed expenses, or overhead expenses. The harvested yield is the output, which is sold to make money. There are several factors that affect the economic analysis of these agricultural crops like geographical location, year of production, the climate of the specific location, commodity prices and costs associated with the production.

The major costs associated with crop farming are seed costs, fertilizer costs, machinery costs, labor, and management costs and land cost. Jack B. Davis, South Dakota State University (SDSU) extension crops business management field specialist, in his article [28] mentioned that for the year 2015, the four corn production costs plus cash rent were 92% of total costs on cash rented corn farmland. The costs incurred with the crops production decreased \$9 for seed, \$21 for fertilizer, \$4 for machinery, and \$8 for labor and management in between 2014 and 2015. Meanwhile, the rent costs decreased by \$17 per acre. In this regard, farmers are facing low to negative margins and will be working for lower costs for 2017 [28].

Seasonality is an important aspect for crop production because it is cheaper to let Mother Nature provide many of the inputs for agricultural production-solar energy, water, carbon dioxide, temperature control, and essential nutrients from natural soils. However, the government should build a proper irrigation and drainage system, which will increase the yield.

Corn uses fertilizer intensively which accounts for around 46 percent of U.S. fertilizer consumption in 2010. Across all crops, the most frequent response to higher fuel prices was to reduce the number of field operations such as tillage, cultivation, or nutrient and pesticide applications that use fuel to run machinery [29]. Inputs like seed, fertilizers, herbicides, fuels, and oil, etc. are directly concerned with the production and can be controlled by the farmer. However, there is a threshold to most inputs where added input use does not increase corn yield. Also, the producers should be sure to include the opportunity cost of the land while doing the economic analysis of the crops [30].

1.7 Aims and Objectives of the Study

The primary objective of this study is to analyze the environmental emissions of three prominent agricultural crop residues from the crop cultivation to the torrefaction process. This study focuses on the environmental sustainability of crops, which can be used as an energy source using the torrefaction process. Therefore, the main goal is to develop a life cycle assessment model using GaBi software.

The specific objectives of this work are listed as below:

1. To compare the environmental impact among corn stover, wheat straw, and soybean residues in terms of global warming potential, acidification potential, eutrophication potential, and emissions to air, water, or soil .
2. To analyze the environmental profile of torrefaction process using crop residues from plant owner perspectives.
3. To study the economic analysis of corn, wheat, and soybean production for South Dakota locality.
4. To find the effect of allocation in the agricultural life cycle analysis.

Therefore, this study emphasizes on the green design of agro-biomass capable of producing torrefied pellets.

1.8 Organization of the thesis

The first chapter gives an overview of renewable energy and sustainable development. Here, life cycle assessment is used as a tool to analyze the quantitative sustainability. This chapter talks about the agricultural life cycle assessment, a tool that assesses the environmental impacts related to agricultural crop production. Moreover, this chapter presents the reader with the economic costs incurred for the crops (like corn, wheat, and soybean) and the socio-economic impacts that the torrefaction process provides for farmers, factory owners and community users. Finally, this is followed by aims and objectives of this study.

The second chapter is the literature review, which details past studies about life cycle analysis and economic analysis of corn, wheat, and soybean. This chapter develops a conceptual framework to understand the torrefaction and life cycle assessment process.

Chapter 3 is dedicated to the methodological framework for the life cycle assessment of the studied system and the comparative analysis for the selected crop residues.

The fourth chapter is the results and discussion section, which explains all the results from the life cycle assessment models. This chapter answers why and how the LCA results help the concerned stakeholders. This chapter presents the evaluation of the environmental consequences of the torrefaction plant system fed with crop residues i.e. corn stover, wheat straw, and soybean residues.

The fifth chapter is the conclusion, which highlights the major findings of the research and future recommendations. This chapter gives a useful perspective to stakeholders in their decision making.

Chapter 2 Literature Review

There has been an increasing focus in agricultural LCAs to see how these crop production affects the environment. This chapter presents the past works that were done in the field of agricultural LCA. Section 2.1 presents an overview of the historical development of torrefaction. Section 2.2 talks about the agricultural biomass and explains the applications of agricultural residues. Section 2.3 elaborates the several types of bioenergy conversion process and describes torrefaction in depth. Similarly, section 2.4 focuses on the environmental concerns related with the conversion of corn stover to torrefied pellets. Section 2.5 emphasizes on environmental sustainability tool, life cycle assessment. Section 2.6 and 2.7 discusses the biomass technology that are prevalent in the developing and developed countries. Moreover, section 2.8 discusses about the market trends of torrefaction in the global perspective. Similarly, section 2.9 is dedicated to the torrefaction companies prevalent in the European and North American scenario. Section 2.10 contains an analysis of the LCA studies on various agricultural crops.

2.1 Historical overview of Torrefaction

People used biomass as a source of food for a long time. Approximately 50% of the world's biomass is used by humans for food plus lumber and pulp and medicines, as well as support for all other animals and microbes in the ecosystem [31]. Later, people began to think about the energy applications of biomass. After the industrial revolution and more specifically after the oil crisis, people thought of using biomass as an alternative energy source. Various thermal-chemical processes like combustion, gasification, pyrolysis, and torrefaction were employed to extract the energy from the several types of biomass (e.g., woody biomass, agricultural residues, and municipal wastes).

A pilot plant for biomass torrefaction was engineered and built in France by the company Pechiney in the mid-1980s, though the torrefied biomass served the purpose of a reducing agent in an aluminum production process and not for energy reasons. However, the plant, with a production capacity of roughly 12,000 tons per annum (t/a), worked well in terms of the technology but still was demounted due to economic aspects in the early 1990s [20].

2.2 Agricultural Biomass

The term biomass refers to non-fossilized and biodegradable organic material originating from plants, animals, and microorganisms. The biomass includes products, byproducts, residues and waste from agriculture, forestry, and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal solid wastes [32].

Biomass is organic matter that can be used to make high-value chemicals, biofuels, recyclable products, animal bedding, pellets, and other products. Biomass is the stored form of solar energy with the photosynthesis process. While biomass emits CO_2 during its use phase, it absorbs CO_2 during the growth phase, so biomass can be taken as CO_2 neutral. One common example of biomass is corn stover. Corn stover is composed of 38-40% cellulose, 28% hemicellulose, 7-21% lignin, and 3-7% ash, on average [33] [34]. Crop residues, including straw, stalk, husk, shell, peel and bagasse, generally have low sulfur and nitrogen content, so they are very suitable for use as feedstocks in the bioenergy supply chain [35].

A wide range of biomass sources such as annual energy crops (e.g., corn, wheat, and soybean), perennial energy crops (e.g., switchgrass, miscanthus, and willow), and agricultural residues (e.g., rice and wheat straw, and corn stover), can be utilized for production of gaseous, liquid and solid biofuels, which can both help reduce fossil fuel consumption and greenhouse gas (GHG) emissions [36].

2.2.1 Agricultural Residues

Agricultural residues are straws, stover, and other plant components remaining in the field after the harvest of a crop. They play a role in maintaining soil health and preventing erosion [37] [38]. Crop residues are also the desirable feedstocks for bioenergy applications because of their low cost, immediate availability, and relatively concentrated location in the major grain growing regions [39]. The primary advantage of using such biomass resource for power generation reside in the chemical-physical characteristics, the consistency in terms of quantity, the distribution almost ubiquitous, and finally, the fact that their production does not threaten the world's food supply [40]. The agricultural residues that can be used as a biomass feedstock can generate revenue for the farmers. Moreover, crop residues protect the soil and control erosion from water and wind, retain soil moisture, increase or maintain soil organic matter, and finally improve crop yields [41]. Otherwise, they are left in the farm or burnt, which may cause environmental pollution. Thus, from the community perspective, establishment of locally available torrefaction facility will minimize greenhouse gas emissions. Moreover, the factory owner can receive the locally available feedstock at a cheaper price.

The characteristics and benefits of agricultural residues capable of torrefaction are listed below as:

- Agricultural residues are homogenous in nature.
- They increase the energy density, and energy performance.
- They improve combustion performance, so superior briquettes and pellets can be formed.
- They can be used as a co-fire fuel to burn with coal.
- They help to reduce the transportation cost of biomass per BTU as torrefaction is done near the point of harvesting.

While agricultural residues are the cheapest and abundantly available resources, they do come with some drawbacks. The low-bulk density of agricultural residues brings difficulty with transportation and storage. Typical bulk density of agricultural biomass and woody biomass is 60–80 and 200–400 kgm^{-3}, respectively [42]. The bulk density of biomass can be increased by forming pellets or briquettes, which results in a final compact density of 600–1,200 kgm^{-3} [43]. Another concern is that when the agricultural residues are removed from the field, the nutrients that have been removed have to be replaced with fertilizers. So, various types of NPK fertilizers are in use. Moreover, another concern may be the crop seasonality due to which there will not be steady supply of crop residues throughout the year.

2.3 Bioenergy Conversion Process

There are mainly four types of thermal biomass conversion technology, namely combustion, gasification, pyrolysis and torrefaction. Combustion means 100% oxidation of all the organic contents of the fuel using air/oxygen, while gasification means partial combustion where 15-30% of the oxygen is added in relation to what would be needed for 100% oxidation. In pyrolysis, we only heat but without adding air and thereby gaseous components of the organic material are evaporated and later condensed as liquid hydrocarbons. Torrefaction occurs when you do partial pyrolysis but only to remove some of the gaseous components, where the purpose is not to produce liquid hydrocarbons but to make a compact residue that can replace coal in coal-fired plants.

2.3.1 Torrefaction

Torrefaction is a thermal pretreatment process to upgrade the properties of lignocellulosic biomass to a high quality ‘‘energy and carbon carrier,’’ which can be effectively used to substitute for fossil fuels [44] [45]. Torrefaction is based on the removal of oxygen from biomass, which aims to produce a fuel with increased energy density by decomposing the reactive hemicellulose fraction [46]. A typical mass and energy balance for woody biomass torrefaction is that 70% of the mass is retained as a solid product, containing 90% of the initial energy content [20]. The other 30% of the mass is converted into torrefaction gas, which contains only 10% of the energy of the biomass. Torrefaction gas can be utilized as a beneficial energy source (utility fuel) in torrefaction in order to improve the overall process efficiency [47] [48].

Torrefaction also has a major potential, as the product is compact and easy to transport long distances in an economical way. The heating value may be up to 25 MJ/kg dry substance, which is in the same range as coal. Another advantage is that the pellets or briquettes produced from torrefied biomass can be used in normal coal mills without having to modify the grinding equipment normally used for the coal. This makes it easy to start using biomass as a complement to coal on a large scale [49].

According to Adams et al. [50], torrefied pellets (TP) offer reduced fossil fuel consumption and greenhouse gas emissions compared to conventional wood pellets (WP) when low-drying energy is assumed, although an increased amount of land is required. Under a high drying energy scenario, TP displayed similar results to WP. Data for particulate matter formation were more uncertain but showed similar impacts for both TP and WP. The flow diagram below shows the working principle of torrefaction starting from the raw biomass (Figure 1).

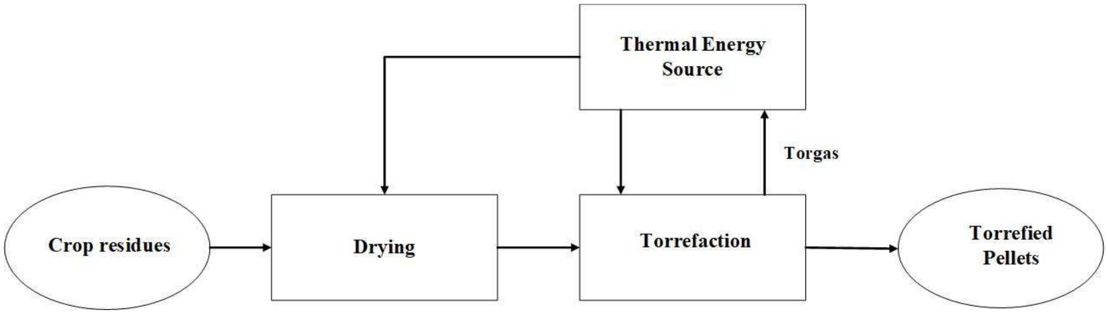


Figure 2-1 Working of torrefaction using crop residues as the feedstocks

2.3.1.1 Applications of Torrefaction Plant

The major applications of torrefied biomass are gasification, co-firing with coal at pulverized-coal-fired power plants, and combustion in pellet burners. The firing and co-firing of biomass in a pulverized coal-fired power plants is expected to increase in the coming years. Torrefaction may prove to be a suitable way of upgrading biomass for such an application. The torrefied biomass will tend to be in pellet form for transport and storage purposes [51]. During the torrefaction process, the tenacious fibre structure of the original biomass is largely destroyed through the breakdown of hemicellulose and to a lesser degree of cellulose molecules, which makes them brittle and easy to grind [52]. Apart from these, in the iron and steel industry, even full replacement of pulverized-coal injection with torrefied biomass injection (150-200kg/t hot metal) could be possible. Torrefied biomass can completely replace coal in a pulverized-coal boiler without a decrease in boiler efficiency. Moreover, replacement of traditional lime-kiln fuels in the pulp and paper industry is possible [53]. Also, the non-metallic mineral industry is willing to use torrefied biomass.

There is a large potential to substitute coal in blast furnaces. The key issues with torrefied material in a blast furnace are the alkali content and composition as well as the high volatile matter content. The steel industry is mainly interested in carbonized biomass, and the application of torrefied biomass seems limited [54]. Power sector along with industry can lead in torrefied biomass's use. Research has proven torrefied biomass as effective for power-plants applications.

Torrefaction is generally done with woody biomass. But, we can also use agri-residues like rice husk, bagasse, saw dust, peanut husk, etc. According to Uslu et al. [22], the use of untreated biomass creates problems due to its susceptibility to microbial degradation, heterogeneous composition, and high bulk volume which complicate process control and logistics management.

2.3.1.2 Benefits of having torrefaction plant

Employment opportunity: There will be lots of job available in the local communities via biomass industry. Firstly, it will motivate the local farmers to produce more crops so that the feedstocks could be sold to the torrefaction plant. There will be effective management of biomass processing in the field. Moreover, the processed agricultural biomass should be transported to collection centers for storage. Finally, these biomasses are transported to the plant, which is used as raw material in a torrefaction plant. Besides, the torrefaction plant need skilled/unskilled manpower for its operation.

Field residues management: Biomass which are left in the field may decay or usually burnt which causes respiratory problems. However, biomass when left could be the field residues for the next crops. In this regard, farmers gained an idea of utilizing the crop residues by selling them (for example, at a harvest rate of 50%-75%) to the locally available torrefaction plant.

Environmental Benefits: Biomass is the raw materials for torrefaction companies. Since biomass is carbon neutral, so it reduces the greenhouse gas emissions. The governmental policy also drives the energy usage of a nation. Nowadays, many countries are focusing on renewable energy sources due to the environmental and health concerns. For example, in Argentina, the legislation has imposed the use of biofuels in blend with fossil fuels (5-10%) in transport fuels [55].

2.3.1.3 End Products from Torrefaction

The primary products produced are solid product of a brown/dark color, condensable liquid (mostly liquid) and non-condensable gases-CO_2, CO, and little amount of methane. The volatiles can be subdivided into condensable and non-condensable compounds. Condensable compounds are mainly water and organic acids, while non-condensable consist mainly of carbon monoxide and carbon dioxide [56]. Based on the applied torrefaction conditions, torrefied biomass is colored brown to dark-brown and approaches the properties of coal [20]. These torrefied biomass can be used for gasification and combustion purposes.

2.3.1.4 Limitations and Gap in Torrefaction

Though various researches based on woody biomass had been done in torrefaction, still optimization of torrefaction has not been completely achieved, which needs to be done for the commercial development of torrefaction technologies. For crop residues there is still a challenge as it ignites easily, has a low bulk density, and has long fibers.

One of the challenges is to see the laboratory experiment in the commercial applications. The efficiency of the plant may not be proportional when the plant size gets increased. The model and prototype torrefactor should be experimentally made in many sizes to see the nature and efficiency of torrefied biomass. Currently, various researches on torrefaction based on agricultural residues put a promising hope though there are various obstacles that need to be studied for the better performance like the various varieties of agricultural residues, moisture content, etc.

2.4 Corn Stover to Torrefied Pellets

The goal of this LCA study is to quantify the energy and GHG impacts associated with the production of corn stover for torrefaction process in SD. The LCA is designed for a cornfield with soils, agro eco-system management, and climatic conditions typical of SD, USA. System boundaries were from cradle to gate and include all the process from corn stover feedstock production to the torrefaction process. Apart, the corn grain is also in use to produce the biofuels which might cause the scarcity of food for the growing population. In this regard, the corn stover can be used as an alternative source for feedstocks to the biofuel industry. The possible uses of corn stover are: animal feed, animal bedding, fuel for a boiler furnace, composite products such as fiberboard, pulp and paper, chemicals, and liquid fuels [57].

For the corn stover to torrefaction process, the crop production and torrefaction process produce direct GHG emissions. Regarding corn production, N_2O emissions from the nitrification and denitrification of nitrogen fertilizers, production of fertilizers and fossil fuel usage in machinery equipment are the major sources of GHG emissions [15]. Apart, GHG emissions from torrefaction are due to the primary energy source used for torrefaction process including the transportation process. Total GHG emissions from corn stover production and transport of stover to the ethanol facility are 320-488 kg CO2e t^{-1} dry stover under 15% stover collection, with SOC loss, N_2O emissions, and stover harvest contributing the most to the total impact [58].

2.5 Life Cycle Assessment

LCA has been used by US and European companies to reduce the products' environmental burdens while improving their financial bottom lines. From the survey of LCA practitioners carried out in 2006, LCA has been used to support business strategy (18%) and R&D (18%), product or process design (15%), education (13%) and for labeling or product declarations (11%) [59]. Thus, the goal of an LCA study is to report as carefully as possible the environmental emissions (air, water and solid waste), raw material, and energy requirements at the boundaries of the system [7].

There has been an increasing focus on how various crops like corn, wheat, soybean, etc. affect the environment. Besides very few studies, most LCAs found a significant net reduction in GHG emissions and fossil energy consumption when bioenergy replaces fossil energy [60]. Cherubini& Strømman, 2011 predicts that the future LCA studies will focus on reducing the uncertainties of the current key open issues, e.g. inclusion in the assessment of indirect land use change effects and their amortization over time, estimation of bioenergy impacts on biodiversity, better determination of fertilizer induced N emissions, and others [60].

Land use change effects, manufacture of additional fertilizers (required to maintain crop yields), and supply of raw materials play the biggest role in the final GHG balance. When agricultural residues are used as feedstocks, best management practices and harvest rates need to be carefully established. In fact, rotation, tillage, fertilization management, soil properties and climate can play an important role in the determination of the amount of crop residue that can be removed minimizing soil carbon losses [61].

LCA deals mostly with the global warming potential, which is the consequences of greenhouse gases (GHGs) production. Some GHGs have a stronger warming effect than CO_2 such as methane with a global warming potential of 25 kg of CO_2 equivalent and nitrous oxide with a global warming potential of 298 kg of CO_2 equivalent. The major greenhouse gases that are accounted for the agricultural LCA are: carbon dioxide, methane, and nitrous oxide. Nitrous oxide is released naturally from soils and water bodies as part of the microbial processes of nitrification and de-nitrification. The two major man-made sources are from agriculture (application of fertilizers to soils and subsequent leaching to water bodies) and the manufacture of acids and nylon. It is also released from power stations and road transport (particularly since the introduction of catalytic convertors) [62].

2.6 Biomass technology in developing countries

Biomass is a major energy source in most of developing countries used for cooking and heating purposes. Due to the unfamiliarity with torrefaction technology and high costs, briquetting techniques is being mostly used in developing countries. The main concern with the briquetting techniques was the smell emanating from the briquettes and the amount of smoke during cooking. While, torrefaction reduce the unpleasant smell and excessive smoke in briquettes.

Among the briquetting techniques, screw press, piston press, and reciprocating type are being used mostly. For reciprocating type, the biomass is pressed in a die by a reciprocating ram at an extremely high pressure. In a screw extruder press, the biomass is extruded continuously by a screw through a heated taper die. In a piston press the wear of the contact parts e.g., the ram and die are less compared to the wear of the screw and die in a screw extruder press. In terms of briquette quality and production procedure, screw press is definitely superior to the piston press technology [63].

People in Rwanda used car engine oil to heat up their biomass. The developed torrefaction technology consists of a thermic fluid system comprising of circulating pump, oil storage tank, furnace, piping, fittings, and instruments. Most countries in sub-Saharan Africa are using their briquetting machines. Most of these machines have been grounded due to high maintenance costs and lack of spare parts [64].

Huge quantity of agro-residues and wastes can be obtained from farming every year. Polak and his team estimated that 1 billion tons of waste is suitable for torrefaction. But Polak mentioned in an interview his vision of designing the torrefaction plants that cost as little as $25,000 [65]. And, with the good incentives and legislations, we can expect the rural villages may go for torrefied biomass depending on the legislations.

2.7 Torrefaction system in developing and developed nations

To produce the torrefied biomass, a wide variety of technologies have been proposed and developed. The reactors used may be horizontal, vertical, moving bed, rotating screws while one developer uses microwaves to heat the biomass [54].

Torrefaction performance depends on the heat integration design and the reactor technology. Mostly, the torrefaction developers use the basic design where the volatiles are combusted in an afterburner and the flue gas is injected to heat the pre-drying process and the torrefaction process. Higher moisture content will increase the residence time of torrefaction.

European torrefaction developers, suppliers and utilities are leading the torrefaction development, with three commercial demonstration plants starting up in the start of 2011 while North American torrefaction initiatives are still in pilot scale phase [66]. Currently in Sweden, biomass contributes about 128TWh, a fifth of total energy supply [67]. The biomass for energy usage is mainly by-products and residues (e.g. sawdust and bark) flow in industrial and agricultural industry [68]. There are a number of innovative technologies in development of torrefaction with thermal fluids of CNFBiofuels (US) and torrefaction combined with washing in the Torwash process of ECN [66]. It seems that most of the project plans of North American torrefaction developers are still in technical and financing phase of realizing commercial plant.

In developing nations, people prefer to use briquetting machines as it is cost friendly and simple to use. Regarding the system development in the developed nation, the activities in torrefaction are laboratory-scale torrefactor, experimental combustion facility, R&D torrefaction pilot project and finally the few commercial torrefactor set up so far.

2.8 Commercialization details and Market Trends about Torrefaction

Torrefaction is now in the commercial phase due to the realization of cleaner fuels. There is huge market of torrefied biomass as it can be used in industrial heating, residential purposes, large- scale power generation, etc. Recently, the market of torrefaction is taken mostly by utilities, which are focusing on renewable energy source in a cost-effective way. Co-firing biomass helps to meet the world's renewable energy targets by making coal-fired plants cleaner without replacing them. The demand of torrefied biomass is being increased than the current production scale. So, the technology and production method need to be scaled up with its optimization.

Despite the favorable properties of torrefied biomass on lab and pilot scale, there are some business and technical challenges that needs to be taken into consideration to develop torrefaction on a business scale. Besides the technological development, product standardization and large-scale product validation are required for the commercialization of torrefaction. Moreover, there are some uncertainties regarding the storage, transport, milling, and combustion of torrefied biomass. Thus, the market of torrefied biomass depends on whether the running torrefaction plants in operation will be able to produce the product that fulfills the expectations [66].

Large number of R&D works has been conducted in the technological advancement of torrefaction during the last few years. There are large number of different reactor and system technologies that has been developed and tested. With increasing energy demands and concerns on clean energy, the governments, policy makers are inclined towards renewable energy. Thus, various industries are focusing on the commercialization of torrefied bimass so as to replace coal.

According to Dahlquist, 2013, of all the 60+ claimed torrefaction initiatives and of all large-scale plants(15+) has been scheduled for start-up during 2010 and 2011, quite few are erected and hardly any has yet reached full stable industrial production and commercial status. Most suppliers tend to exaggerate their capacities and underestimate time and efforts needed. Torrefaction has to be done intelligently, cost-effectively and thoroughly for commercialization progress and success. The material produced should be completely homogenous in terms of torrefaction degree and preferably dark brown (not overtorrefied) for a sufficient yield and to facilitate densification. Nevertheless, a few initiatives are hopefully paving the way for the torrefaction industry. There are four torrefaction demonstration plants up and running in Europe like Stramproy Green (Netherlands), Amel (Belgium), Topell Energy and RWE Innogy GmbH (Duiven, Netherlands) and Torr-Coal Group (Belgium). And at least 7 more demonstration plants are scheduled for startup during 2012/13. Some North american initiatives with torrefaction processes are: Agri-Tech Producers, Integro Earth Fuels, River Basin Energy, Torrsys and Wyssmont. Moreover, most developers are also operating pilot-plant processes based on their preferred technology [49].

It seems that the market price of torrefied biomass depends on the cost price as well as the result of negotiation between supply and demand. Only when significant commercial production starts up and trade volume increase will the true market value of torrefied pellets or briquettes be established. Moreover, the quality control and quality assurance standards will have to be introduced for the proper tracing of materials and products [54].

2.9 Torrefaction initiatives

Given below is the list of torrefaction industries with their location, established date, capacity, and the technology they employed.

Table 2-1 Details of torrefaction industries

Torrefaction developer	Initiation date	Location	Production capacity(t/a)	Technology
Topell Energy B. V. (NL)	2010	Duiven, Netherlands	60,000	Torbed
Stramproy Green Investment B.V.	2010	Steenwjik, Netherlands	45,000	Oscillating belt conveyor
4Energy Invest	2010	Amel, Belgium	38,000	
Torr-Coal B.V.	2010	Dilsen-Stokkem,belgium	35,000	Rotary Drum
Thermya(FR)	2011	San Sebastaian, Spain	20,000	Moving Bed
FoxCoal B.V.	2012	Winschoten, Netherlands	35,000	Screw Conveyor
BioLake B.V.	2010	Eastren europe	5,000-10,000	Screw Conveyor
EBES AG(AT)	2011	Frohnleiten, Austria	10,000	Rotary drum
Atomsclear SA	2010	Latvia, New Zaealand, US	50,000	Rotary Drum
Bio Energy Development North AB	2011/2012	Örnsköldsvik, Sewden	25,000-30,000	Rotary Drum
Rotawave, Ltd.	2011	Terrace British Columbia(CA)	110,000	Microwave reactor
Integro earth fuels, LLC	2007	Roxboro, NC, USA	50,000	TorboDryer
Agri-Tech Producers LLC	2010	Kusters Zima Corporation, SC, USA		Belt reactor
Torrefaction Systems Inc. (US)	2013			
New Earth Renewable Energy Fuels, Inc. (US/WA)				Fixed bed
Zilkha Biomass Energy	2010	Crockett, Texas, USA	40,000	
WPAC(CA)	2011		35,000	

2.10 LCA Studies on agricultural crops

Agriculture has several aspects that need to be considered. The agricultural LCA studies the effects on water bodies due to the fertilizer runoff, global warming potential due to the combustion of gasoline and diesel, eutrophication, etc. For this, the efficient LCA databases and calculation procedures are required. However, some of the agricultural processes that are difficult to control are nutrient leaching, erosion, N_2O emissions, etc. Thus, LCA provides good insights into the behavior of the systems.

Agrarian systems belong to the most complex production systems due to the determinant influence of environmental conditions which varies with time and space at a high spatial heterogeneity of site conditions [25]. Some of the key features of agricultural model in GaBi ts are listed below:

- This is a mixed balance model with different implicit mapped compartments and a simplified time resolution.
- This is a flexibly usable model.
- It is also highly parameterized and is provided with many background processes.
- And finally, it is applicable for any agrarian and plantation product of the world [25].

One of the research studies conducted in the Netherlands concludes that co-firing and transportation stages contribute the most regarding three environmental impacts namely global warming, acidification, and photochemical oxidation potentials. This study shows that torrefied biomass co-firing chain can be considered the best option when Dutch biomass is utilized. The reduction is approximately 12% for global warming, 7% for acidification and 5% concerning photochemical oxidation potentials [69]. Moreover, Perez et al. [70] demonstrated that cofiring coal with biomass is a very attractive alternative to reduce environmental impacts associated to electricity generation in Chile.

Chapter 3 Methodology

A variety of biomass can be used as a raw material for torrefaction production, e.g., agricultural residues, forest residues, municipal wastes, etc. This study focuses on the potentiality of the agricultural residues as the feedstocks for the torrefaction companies. This chapter explains the methodological approach, which discusses the life cycle assessment of crop production and crop residues based torrefaction as well as techno-economic analysis of corn, wheat, and soybean production. The environmental assessment framework puts LCA in context and describes how this tool can be used for the environmental assessment of crop production and crop residue based torrefaction. Thus, this third chapter is the methodological section that focuses on the LCA procedures based on the ISO framework (ISO 14040 and ISO 14044 standards).

3.1 Life Cycle Assessment Framework

This research study adopts the principles and guidelines of ISO 14044:2006 as per the International Organization for Standardization. ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment (LCA), which includes definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements [71].

This research methodology arises various key questions. Will the torrefaction process cause scarcity of crop residues? Will this process cause an impact on ecosystems? What may be the emissions from the torrefaction process? It is obvious that the energy requirement is increasing due to the population growth. So, people are focusing on renewable energy sources to fulfill the demand on energy. In this regard, torrefied pellets may be a sustainable alternative to replace coal. Since coal is one of the greatest CO_2 emitting fuels, so we need to reduce the use of coal by replacing it with biomass (partially) in the long-run. For this, the sustainable alternative may be the torrefied wood, torrefied pellets, low emissions biomass or cofiring any one of these with coal.

LCA is a suitable tool to study the sustainability of the environment, where we can study the potential impacts from the agricultural activities. As recommended by ISO, LCA study can be carried out in four steps:

1. Goal & Scope Definition
2. Life Cycle Inventory Analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Life Cycle Interpretation

The relationship between the four stages of LCA is shown in Figure 3-1:

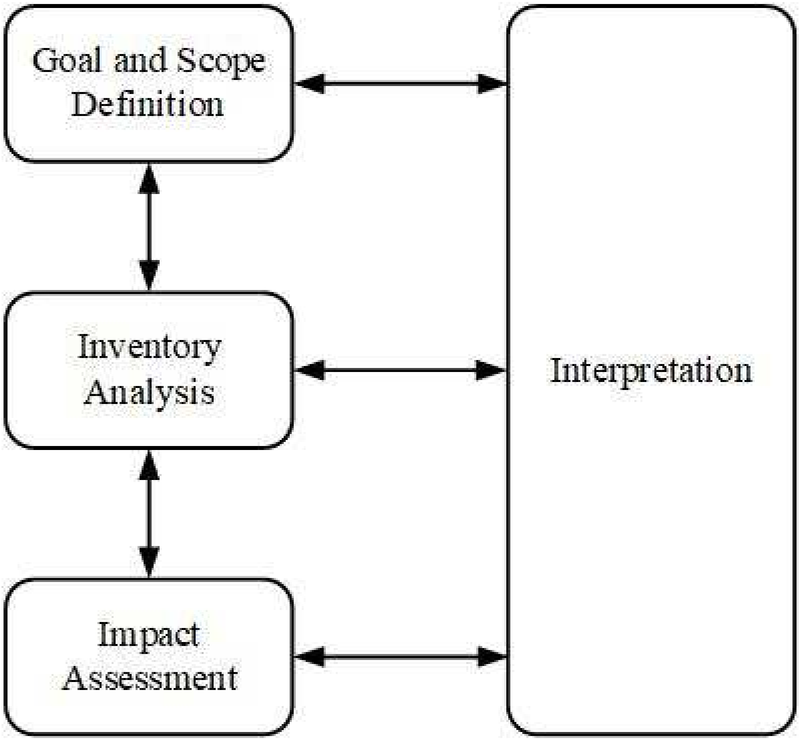


Figure 3-1 LCA phases

Figure 3-1 shows that LCA is an iterative process, which denotes that the changes made in one phase of LCA will affect the other phases. LCA is an important decision-making tool for the various stakeholders such as factory owners/managers, farmers, community members, businesspeople, etc. There are various requirements for a successful LCA study. The goal and scope of the LCA study should be clearly defined with correct boundaries and assumptions. The LCA analyst should look at all the aspects of production. Therefore, a prominent level of technical knowledge is needed. The data taken should be from reliable sources, so it can properly address the developed model.

3.2 The Agricultural LCA Model

Agricultural LCA is often complex because in addition to the main product, there are usually coproducts, so that appropriate environmental impacts need to be assigned to each product, a process known as allocation. There may also be by-products or waste and emissions to the environment, for example nitrate (NO_3) to water and nitrous oxide (N_2O) to the air [72].

This study focuses on the life cycle assessment of torrefaction process using agricultural feedstocks, which finally help to find the environmental hotspots. The LCA was performed based on the ISO 14044 using GaBi ts software. The data for inputs, outputs, and emissions involves numerous issues. The database used in the life cycle modeling of these projects were taken from the U.S. Life Cycle Inventory Database [73], which were accessed with the help of life cycle assessment software, GaBi ts. GaBi databases are the third-party life cycle databases. Moreover, the energy datasets that were considered for the upstream and downstream processes in the crop production projects were validated from the background analysis of the energy data for the life cycle database [74]. Since most of the database is based on European and North-American scenarios, this study looks upon the most relevant data for each process involved and try to reflect the actual scenario of our location, South Dakota. The agricultural costs that were considered include electricity cost, fertilizers costs, lime (quicklime) costs, fuel costs, transportation costs, etc.

The simple layout of the cradle-to-gate approach used in our agrarian system is shown in Figure 3-2:

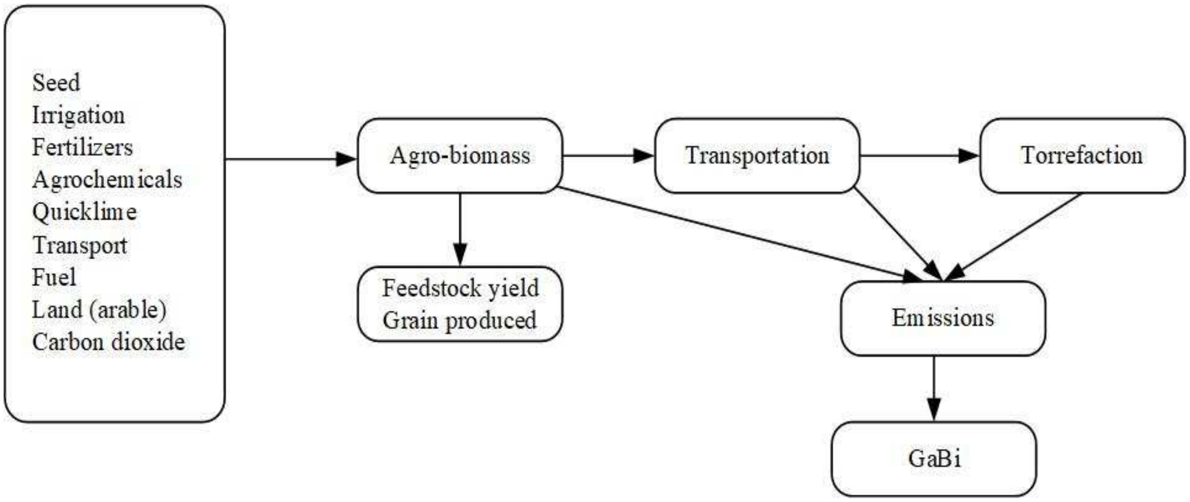


Figure 3-2 Cradle-to-gate system boundary

Figure 3-2 is the simplified block diagram, which shows the cradle-to-gate system boundary starting from the raw materials to the production of torrefied pellets. In this study, the end use of torrefied pellet is not considered.

3.2.1 Goal & Scope definition

This is the key step, which articulates the objectives of the LCA study. Thus, the goal and scope need to be clearly defined. Assumptions made during the study should be clearly stated. Similarly, the system boundary and functional unit should be clearly mentioned. The goal of LCA shall include motivations for the study, intended applications and audiences, initial data quality requirements, and type of critical review [75]. Moreover, the scope should be well defined to make sure that the breadth, depth, and detail of the study are compatible and sufficient to address the stated goal [8]. Since LCA is an iterative process, the goal and scope can be redefined depending upon the LCA modeling.

The goal of this study is to analyze the ‘cradle-to-gate’ LCA approach of the agricultural crops and torrefaction process. The stakeholders associated are the feedstock producers, torrefaction plant owners, and the community members. The site selected for the LCA study was Brookings, South Dakota.

3.2.1.1 Assumptions

The distance from the field to the torrefaction plant was taken as 100km. The baled residues were transported using GLO: Truck of 7.5-12 tons of gross weight with a payload capacity of 5 tons. The thermal energy needed for torrefaction process was provided from natural gas. Land use change was not included in this LCA study due to the lack of data. TRACI methodology was employed for the environmental impacts assessment.

3.2.1.2 System Boundaries

This describes the unit processes that have been included and excluded in the LCA study. The crops taken for the LCA analysis are corn, wheat, and soybean. These crops are the main crops produced in the Midwest region of USA. There are four main options to define system boundaries for an LCA study.

1. Cradle-to-Grave: It includes the LCA from raw material to disposal phase. Thus, it helps to address the potential environmental impacts of a product or a service from the initial phase to the end of life stage.
2. Cradle-to-Gate: It includes the environmental assessment from raw materials to production phase. Therefore, it is used to assess the environmental impact of the production of a product in a factory gate (no use or end-life considerations). Practitioners have historically handled the complexity of LCI and LCA studies by developing “cradle-to-gate” subsystems that are complete and self-standing. For

example, the life-cycle steps from iron ore mining through steel wire manufacture represent the cradle-to-gate segment for the manufacture of steel wire [7].

3. Gate-to-Grave: This emphasizes the LCA from production to the disposal stage.
4. Gate-to-Gate: This covers the LCA study through the production phase only ("gate of the factory"). Here, we consider taking products and raw materials from the entrance gate of a manufacturing plant to the finished product leaving the shipping gate (only onsite emissions).

After harvest, the crop residues like corn stover is collected and transported to the torrefaction facility. The farm equipment production systems are excluded from the system boundary because of their small contribution to the overall impact [76]. Transportation of biomass to the torrefaction facility is being included in this system. Environmental impacts associated with the physical and human capital (i.e. the production and maintenance of building infrastructures and vehicles, labor, and associated resources) were not included in the model. Moreover, the use phase (combustion of torrefied pellets) is not included as the system boundary ends with the production of torrefied pellets.

The ISO 14044 standard details the choice of a system boundary for LCA studies [6].

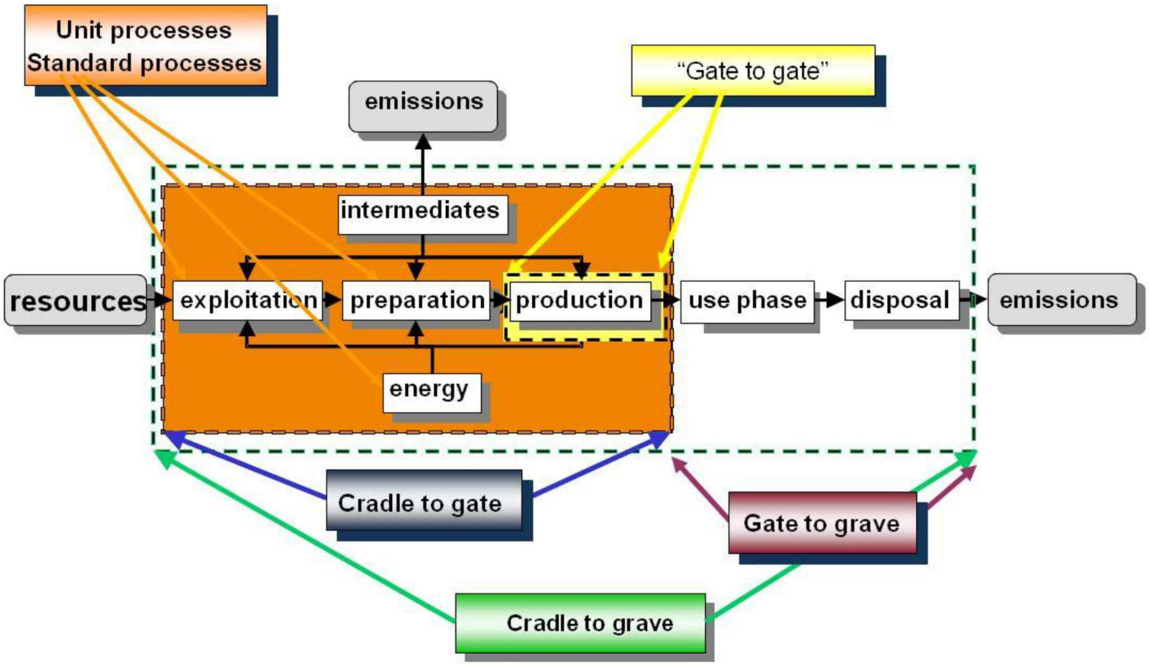


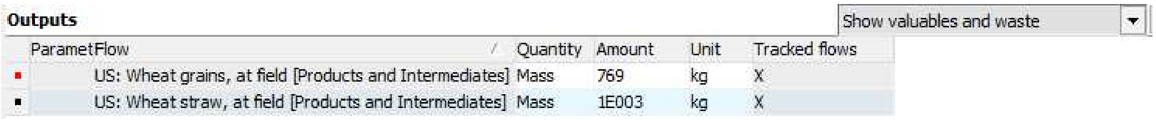
Figure 3-3 System Boundaries

3.2.1.*3* Functional Unit

The function of the studied system is to produce the agricultural crop residues and use these residues for torrefied pellets production. So, the functional unit considered in this study is the amount of agricultural residues that come from the harvest of agricultural crops, i.e. corn, wheat, and soybean. For the comparative study, the functional units chosen should be equivalent. The functional unit is yield produced for most of the agricultural LCAs [77].

3.2.1.4 Allocation

Allocation is the process of dividing the environmental impacts from the processes based on the main products and coproducts. This is a key step in agricultural life cycle assessment. In this study, crop residues comprise the main products since these crop residues were used to produce torrefied pellets. The allocation procedure was performed based on the weight of the products. Analysis was done with and without allocation as shown in the figure 3-5 and figure 3-4 respectively.

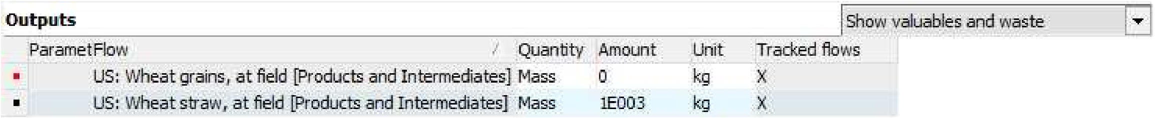


Outputs

Show valuables and waste

ParametFlow	Quantity	Amount	Unit	Tracked flows
US: Wheat grains, at field [Products and Intermediates]	Mass	769	kg	X
US: Wheat straw, at field [Products and Intermediates]	Mass	1E003	kg	X

Figure 3-4 No allocation in between grains and residues



Outputs

Show valuables and waste

ParametFlow	Quantity	Amount	Unit	Tracked flows
US: Wheat grains, at field [Products and Intermediates]	Mass	0	kg	X
US: Wheat straw, at field [Products and Intermediates]	Mass	1E003	kg	X

Figure 3-5 Allocation of crop residues based on dry weight

3.2.2 Life Cycle Inventory

The main purpose of the life cycle inventory (LCI) is to identify and quantify the energy, water and material usage, and environmental releases (e.g. air emissions, solid waste disposal, and wastewater discharges). LCI analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system [50]. There are precise guidelines (SETAC 1993, ISO 14041 1998) for LCA practitioners about how to make key decisions related to the definition of the system and their boundaries, the definition of the functional units, the data collection and calculation procedures, particularly for what energy accounting and allocation rules are concerned [78].

The numerous ways for data sources that could be employed were direct measurement, literature review, interview, LCI databases such as USLCI, Ecoinvent, etc. After collecting all the process data, the LCI table is created for the convenience to reflect the inputs and outputs that are used for the LCA modeling. This is a crucial phase in the LCA study. Thus, to keep the consistency in the LCI, the data collection has been done from the USLCI databases for all the studied crops. Moreover, data for the crop harvest rate and thermal energy were obtained from the relevant literature.

3.2.3 Life Cycle Impact Assessment (LCIA)

LCIA assigns the results of the life cycle inventory to impact categories, which are classes being different environmental issues of concern. LCIA has three mandatory phases (ISO 14042-2000): selection of impact categories, category indicators and characterization models, assignment of LCI results (classification) and calculation of category indicator results [78]. The inputs and outputs are first assigned to impact categories and their potential impacts are quantified as per the characterization factors [6].

In the LCIA models, such as TRACI or CML, two main approaches are used to classify and characterize environmental impacts: the problem-oriented approach (mid-point) and the damage-oriented approach (end-point). The problem-oriented approach classifies flows as belonging to environmental impact categories to which they contribute. TRACI adopts problem-oriented approach and is developed by U.S. Environmental Protection Agency (EPA) and is primarily used in the US [6]. Thus, TRACI method was selected to study the impact categories like global warming potential (kg CO_2 eq.), acidification potential (kg H+ moles eq.) and eutrophication potential (kg N eq.). The choice for these impact categories is goal dependent.

TRACI 2.1 was selected as it is currently the only impact assessment methodology framework which incorporates US average conditions to establish characterization factors [79]. LCIA results are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks [80].

Impact Categories:

Some of the frequently used impact categories, their respective units and consequences are shown in the Table 3-1.

Table 3-1 Impact categories used in LCA

Impact categories	Units	Consequence
Global warming potential (GWP)	CO_2 eq. (kg)	Global Warming
Acidification Potential (AP)	H+ mole eq. SO_2 eq. (kg)	Acid Rain/Forest Decline
Eutrophication Potential (EP)	Kg N eq. PO_4 eq. (kg)	Over fertilization of soil or water
Ozone Layer Depletion (OLD)	CFC 11 eq. (kg) R_{11} eq. (kg)	Thinning of ozone layer in the upper atmosphere
Photochemical Ozone Creation Potential (Summer Smog)	ethene eq. (kg)	Ozone formation in the lower atmosphere

3.2.4 Interpretation

This is the final stage, where the inventory analysis and the impact assessment are compiled into results. This is the phase, where the LCA practitioners can look upon the study’s accuracy, limitations, uncertainty, etc. The LCA results are acceptable for the designed system by its cope and boundaries. GaBi provides the balance button, which helps to calculate the LCA results and lists all the inputs and outputs from the life cycle analysis. Various analysis like scenario analysis, sensitivity analysis, Monte Carlo simulation, and parameter variation can be done from the parameter explorer in GaBi.

While, in this study, we focus on the comparative assessment of three crops i.e. corn, wheat, and soybean and draw a conclusion based on impact categories like global warming potential, acidification potential, and eutrophication potential. Also, we looked upon the torrefaction process, which uses crop residues as the raw materials and processed into the torrefied pellets. The results from the LCA model were discussed in the results and discussion section in depth.

3.3 LCA Modeling

This study was performed using LCA software, GaBi, which incorporated the USLCI databases, Ecoinvent databases, and databases from the various literature review. GaBi ts educational version was used for this study. To understand the working phenomenon within GaBi, the user should be familiar with few terminologies such as: project, plans, processes, flows, quantities, etc. The project can be first defined and activated in GaBi. For each of these projects, new plans were generated. A life cycle assessment model was generated in the plan window. The plan consists of various processes which were linked to relevant flow parameters by giving input and output parameters.

GaBi checks for input and output matches between the two adjacent processes. Afterwards, the flow can be properly defined between the different processes. The USLCI database was used for this modeling and calculation. After the model was developed in GaBi, the balance button was used to see the environmental impact assessment. GaBi shows the results for different assessment methods like ILCD recommendations, LCIA-

CML 2001 (Nov 10), LCIA-TRACI, LCIA and ReCiPe. LCIA-TRACI was chosen for this study since this methodology has been widely used in the US.

In this study, the LCA has been employed to evaluate the environmental impacts of torrefied pellets and crop residues (corn stover, wheat straw, and soybean residues) from the viewpoint of farmer and torrefaction plant owner. Here, life cycle analysis was performed to analyze the results in terms of emissions to air, water, soil, etc.

Below are the strategic ways to tackle the research method.

- Choose the potential biomass
- Define the process
- Use LCA Modeling
- Interpret Results

The torrefied pellets discussed here are made using the crop residues. The amount of grain produced, and crop residues are different based on the crop that were harvested. Table 3-2 shows the quantitative relationship between the amount of crop grains and crop residues.

Table 3-2 Quantitative relationship between grains and crop residues

Grains to crop residues	**Ratio (by mass)**
Corn grains to corn stover	1:1
Wheat grains to wheat straw	1:1.3
Soybean grains to soybean residues	1:2.1

The first section illustrates the LCA conducted on torrefaction using crop residues i.e. corn stover, wheat straw, and soybean residues. Similarly, the second section describes the LCA of three major agricultural crops namely corn, wheat, and soybean. Moreover, the mass and energy balance of torrefaction process is shown in Figure 3-6.

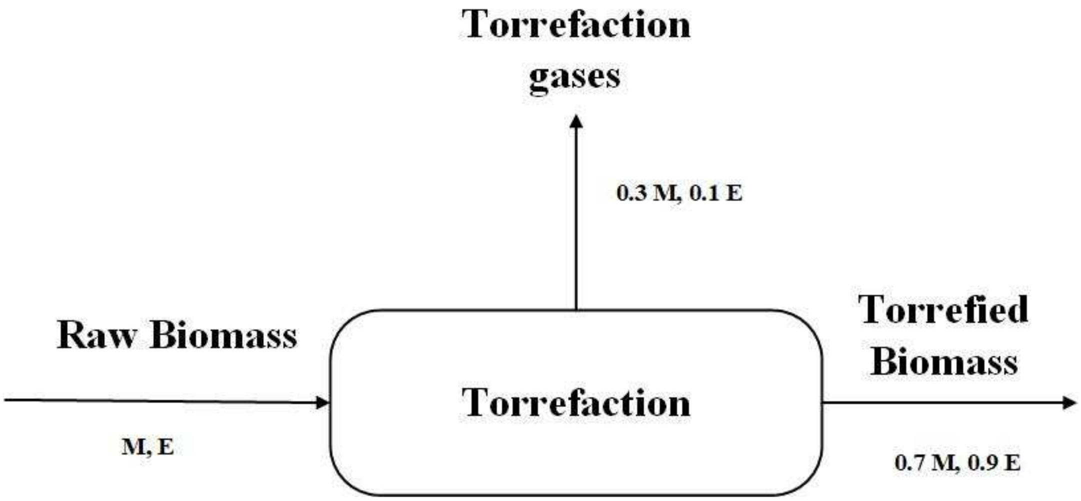


Figure 3-6 Mass and Energy balance of torrefaction process

Fig 3-6 provides a typical mass and energy balance for biomass torrefaction. Here, 70 % of the mass is retained as torrefied biomass, which contains 90% of the raw biomass energy content [47]. Another important concern with the torrefied biomass production is that the torrefaction gas is recirculated, which lowers the fuel requirement for drying and torrefaction processes.

The projects that were created in GaBi are described below in detail.

3.3.1 Corn Stover Torrefaction: SD

The goal of this study is to assess the environmental impacts of corn stover grown in SD that can be used to produce torrefied pellets. Corn stover appears to be a promising source of biomass for biofuel production, since it does not directly compete with food and is grown in large quantities during corn production [81]. The function of this study is to analyze the environmental impacts from the torrefaction process using corn stover. Thus, the functional unit is the quantity of agricultural residues produced from an acre of land (considering harvest rate of 50%). They were set to meet erosion tolerances with a maximum of 50% stover removal. It is reasonable to consider that, in many instances, the stover removal rates used in this study would be acceptable and keep erosion within the tolerable limits [82]. The system boundary considered here is cradle-to gate. The data inventory required for the various processes and input/output parameters were taken from the available literature and USLCI databases. Various processes were defined and connected by the flow parameters, which is illustrated below in Figure 3-7.

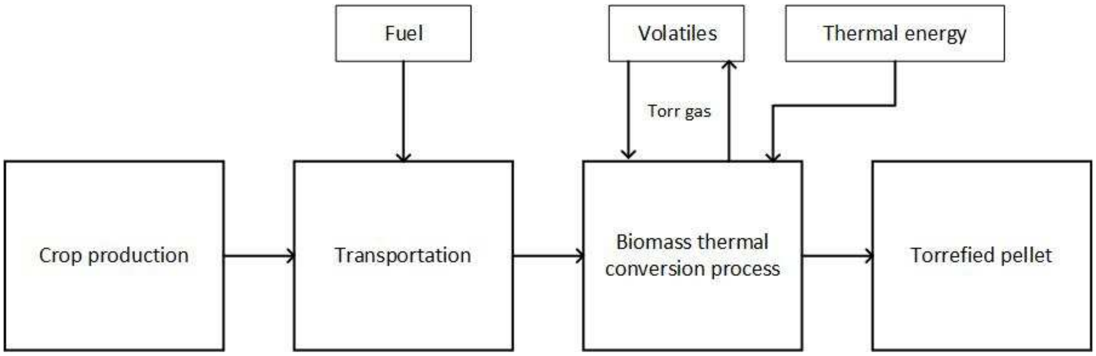


Figure 3-7 LCA model for torrefaction

The LCA modeling was developed in GaBi ts. Since the study was conducted for Brookings, SD, so the yield of crops was taken for this region. A yield of 160 bushels (4064kg) of corn grain was assumed. Also, the harvested percentage of corn stover was assumed to be 50%. The ratio of corn grain produced and harvested corn stover was taken 1:1. The reference quantity used was mass. A GLO truck with a payload capacity of 5t was used for the transportation process, which consumed 8.57 kg of diesel. The trucking distance was taken to be 100km. The thermal energy required for torrefaction is taken as

2250 KJ/kg of biomass [83]. Natural gas was taken as the thermal source of energy for the drying and torrefaction processes. Moreover, the mass of torrefied pellets was 70% of the original biomass. Therefore, the mass of the volatiles coming out of the torrefaction process will be 30% of the original biomass.

Fig 3-7 shows the LCA modeling for the crop residues to torrefied biomass production process. The life cycle of this crop residues to torrefied biomass is divided into three stages.

1. Crop Production
2. Transportation
3. Torrefaction

3.3.2 Wheat Straw Torrefaction: SD

The goal of this study is to assess the environmental impacts of wheat straw grown in SD that can be used to produce torrefied pellets. The function of this study is to analyze the environmental impacts from the torrefaction process using wheat straw. Thus, the functional unit is the quantity of agri-residues produced from an acre of land. Cradle-to gate system boundary was used for this analysis. The data inventory required for the various processes and input/output parameters was taken from the available literature, USLCI databases and GaBi databases.

A yield of 60 bushels (1632kg) of wheat grain was assumed. This is the amount of wheat grain production in Brookings, SD. The ratio of wheat grain produced, and harvested wheat straw was taken as 1:1.3. The harvest rate used for wheat straw was 66% [84]. The reference quantity used was mass. A GLO truck with a payload capacity of 5t was used for the transportation process, which consumed 5.91 kg of diesel for the transportation distance of 100km. The thermal energy consumption required for torrefaction of wheat straw is taken to be 2250KJ per kg of wheat straw [83].

3.3.3 Soybean Residues Torrefaction: SD

The goal of this study is to analyze the environmental impacts of soybean residues that can be used to produce torrefied pellets. The function of this study is to analyze the environmental impacts from torrefaction process using soybean residues. Thus, the functional unit is the amount of soybean residues that can be harvested from one acre of land. The harvest rate used for the soybean residues was 40% [84]. Cradle-to gate system boundary was used for this analysis. The data inventory needed for the various processes and input/output parameters were taken from USLCI databases, GaBi databases, and literature review. The thermal energy was provided with the natural gas which consumed 2250 kJ per kg of raw biomass utilized [83].

Similarly, the three other LCA models for crop production that were developed in GaBi are described below with the help of block diagram as shown in Figure 3-8.

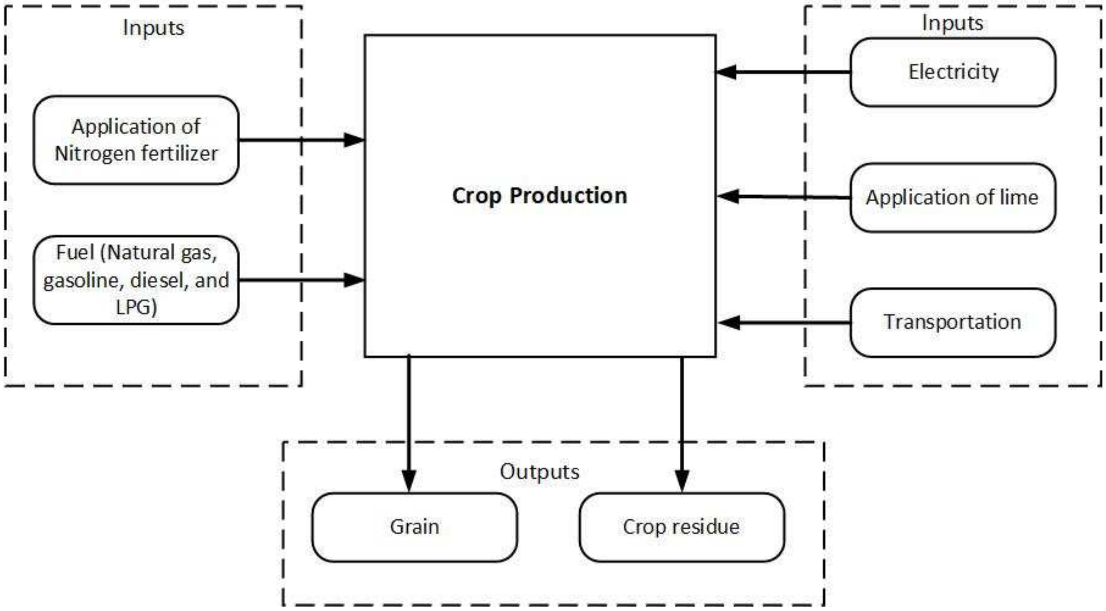


Figure 3-8 Inputs and Outputs from the agrarian system

The LCA modeling of the agrarian system is a complex network making up of all the upstream operations associated with the nitrogen fertilizer production, lime production, fuel combusted, electricity, etc. Inputs for nitrogen fertilizer production at plant is modeled, as shown in Figure 3-9.

Figure 3-9 Unit processes for nitrogen fertilizer production at plant

Similarly, lime (quicklime) production process is modeled as shown in Figure 3-10.

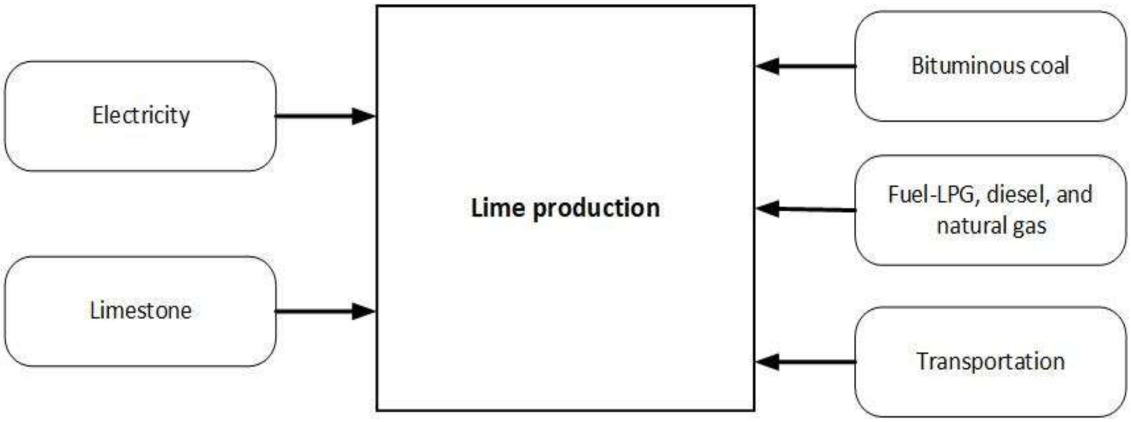


Figure 3-10 Unit processes for lime production at plant

3.3.4 Corn Production

Corn production includes various processes such as use of machinery equipment's, combustion of fuel (diesel, gasoline, liquefied petroleum gas, and natural gas), application of fertilizers and lime, etc. The developed LCA model consists of most of the upstream processes associated with the processes. All the associated processes were developed for the US scenario. The LCI table for the corn production is shown in Table 3-3.

Table 3-3 Life cycle inventory table for corn production

Flow	**Quantity**	**Amount**	**Unit**
Electricity [Electric power]	Energy (net calorific value)	0.022	MJ
Lime quicklime (lumpy) [Minerals]	Mass	0.0152	kg
US: Diesel, combusted in industrial equipment [Products and Intermediates]	Volume	3.4301E-6	m^3
US: Gasoline, combusted in equipment [Products and Intermediates]	Volume	9.405E-7	m^3
US: Liquefied petroleum gas, combusted in industrial boiler [Products and Intermediates]	Volume	2.4363E-6	m^3
US: Natural gas, combusted in industrial boiler [Products and Intermediates]	Volume	0.0015254	m^3
US: Nitrogen fertilizer, production mix, at plant [Products and Intermediates]	Mass	0.00844	kg
US: Transport, single unit truck, diesel powered [Products and Intermediates]	kgkm	8.26	kgkm
US: Transport, train, diesel powered [Products and Intermediates]	kgkm	22	kgkm
US: Corn, at field [Products and Intermediates]	Mass	0.5	kg
US: Corn stover, at field [Products and Intermediates]	Mass	0.5	kg

Table 3-3 shows the inputs and outputs of the corn production. The valuable inputs taken for the corn production were the fuel combusted (e.g., diesel, gasoline, natural gas, and liquefied petroleum gas), nitrogen fertilizers, quicklime, electricity, truck, etc. This inventory table was developed for 0.5kg of corn grain production, which produced 0.5kg of corn stover.

3.3.5 Wheat Production

Wheat production also consists of various upstream processes like the manufacture of fertilizers and lime, electricity production, transportation, etc. Similarly, it includes the downstream operations such as application of fertilizers, use of machinery equipment's, etc. This LCA model looks up for most of the significant agricultural processes. All the processes modeled were considered for the US scenario. Table 3-4 shows the LCI table that was used for the modeling of the wheat production.

Table 3-4 Life cycle inventory table for wheat production

Flow	**Quantity**	**Amount**	**Unit**
Lime quicklime (lumpy) [Minerals]	Mass	0.0187	kg
US: Diesel, combusted in industrial equipment [Products and Intermediates]	Volume	1.7177E-5	m^3
US: Gasoline, combusted in equipment [Products and Intermediates]	Volume	3.9038E-6	m^3
US: Nitrogen fertilizer, production mix, at plant [Products and Intermediates]	Mass	0.0285	kg
US: Transport, single unit truck, diesel powered [Products and Intermediates]	kgkm	20.4	kgkm
US: Transport, train, diesel powered [Products and Intermediates]	kgkm	54.3	kgkm
US: Wheat grains, at field [Products and Intermediates]	Mass	1.0	kg
US: Wheat straw, at field [Products and Intermediates]	Mass	1.3	kg

As per the table 3-4, the inputs that were used for the wheat production were quicklime, diesel, gasoline, nitrogen fertilizers, diesel powered truck, diesel powered train, etc. The valuable outputs were the wheat grains and the wheat straw. From the inventory table, we can see that 1 kg of wheat grain production results 1.3 kg of wheat straw.

3.3.6 Soybean Production

As discussed for corn and wheat, soybean production also includes the similar processes for the growth and cultivation. Lime contributes significantly (17% of the total emissions) to NO_x emissions in soy production and therefore they are considered in bioproduct LCA [13]. Table 3-5 shows the valuable inputs and outputs for the soybean production.

Table 3-5 Life cycle inventory table for soybean production

Flow	**Quantity**	**Amount**	**Unit**
Electricity [Electric power]	Energy (net calorific value)	0.0191	MJ
Lime quicklime (lumpy) [Minerals]	Mass	0.0836	kg
US: Diesel, combusted in industrial equipment [Products and Intermediates]	Volume	1.7056E-5	m^3
US: Gasoline, combusted in equipment [Products and Intermediates]	Volume	7.9593E-6	m^3
US: Liquefied petroleum gas, combusted in industrial boiler [Products and Intermediates]	Volume	7.1023E-7	m^3
US: Natural gas, combusted in industrial boiler [Products and Intermediates]	Volume	0.00050205	m^3
US: Nitrogen fertilizer, production mix, at plant [Products and Intermediates]	Mass	0.0011415	kg
US: Transport, single unit truck, diesel powered [Products and Intermediates]	Kgkm	17.4	kgkm
US: Transport, train, diesel powered [Products and Intermediates]	Kgkm	46.4	kgkm
US: Soybean grains, at field [Products and Intermediates]	Mass	1.0	kg
US: Soybean residues, at field [Products and Intermediates]	Mass	2.1	kg

This inventory table shows the inputs and outputs associated with the soybean production which produces 1 kg of soybean grains and 2.1 kg of soybean residues.

Chapter 4 Results and Discussion

This chapter explains the main findings of the research study, which answers the key questions formulated in the aims and objectives section of the chapter 1. Section 4.1 identifies the main expenses related with the crop production and describes the economic analysis of crops. Similarly, section 4.2 and 4.3 are dedicated in summarizing the environmental impacts of crop production and crop residues based torrefaction. Section 4.4 shows the environmental assessment of the crop rotation namely corn, wheat, and soybean. Section 4.5 discusses the implications of harvesting crop residues for torrefaction. Moreover, section 4.6 gives the idea about the farming practices for corn, wheat, and soybean in SD locality. Finally, section 4.7 talks about the validation of the used LCA method and the results. Thus, LCA framework has been developed as a means of decision-making for the concerned stakeholders.

4.1 Economic Analysis of Corn, Wheat and Soybean production

The economic analysis of these major agricultural crops was done in Excel sheet. The location selected for the study was Eastern and Central SD, Brookings. Judging from the past years' studies, the production yield was assumed to be medium (may be high, medium, or low). One acre of land served as the basis for this economic analysis. Table 4-1 shows the expenses associated with the crops production, income generated, and profit with and without considering the land cost.

Table 4-1 Economic analysis of corn, wheat, and soybean

	Corn	Soybean	Wheat (Winter)
Number of bushels produced	160	45	60

Cost/bushels	$ 3.10	$ 9.10	$ 4.30
Income	$ 496	$ 409.5	$258
Seed	$ 81	$ 54	$ 13
Fertilizer	$ 71	$ 28	$ 65
Pesticides	$ 26	$ 30	$ 16
Crop Insurance	$ 22	$ 19	$ 17
Fuel & Oil	$ 22	$ 21	$ 14
Repairs	$ 30	$ 16	$ 13
Custom Hire			$ 38
Drying	$ 22		
Operating Interest	$ 10	$ 6	$ 6
Machinery (Ownership Costs)	$ 56	$ 56	$ 35
Management Costs	$ 41	$ 41	$ 41
Total expenses before land charge	$ 381	$ 271	$258
Land Cost	$ 193	$ 193	$ 193
Without accounting land cost	Profit = $ 115	Profit = $ 138.50	
With Land Cost	Loss = $ 78	Loss= $ 54.50	Loss = $ 193

The yields for corn, wheat, and soybean were considered 160 bushels, 60 bushels and 45 bushels, respectively for an acre of land. Various expenses related to the agricultural production, such as the cost of seed, fertilizers used, pesticides, fuel and oil, drying, repairs, custom hire, operating interest and machinery costs, were also part of the analysis. Finally, the profit from the crop production was calculated with and without considering of land cost. Thus, we can say that soybean is more profitable than corn and wheat. Also, the cost for an acre of land was assumed to be $193. However, while accounting for the land cost, there seems to have been a loss for each crop's production. In such cases, the farmers need to reduce the agricultural expenses and adopt scientific farming techniques for better yields to make greater profits.

Bar graph that portrays the economic analysis of corn, soybean, and wheat production for an acre of land in Eastern & Central South Dakota, Brookings are shown below.

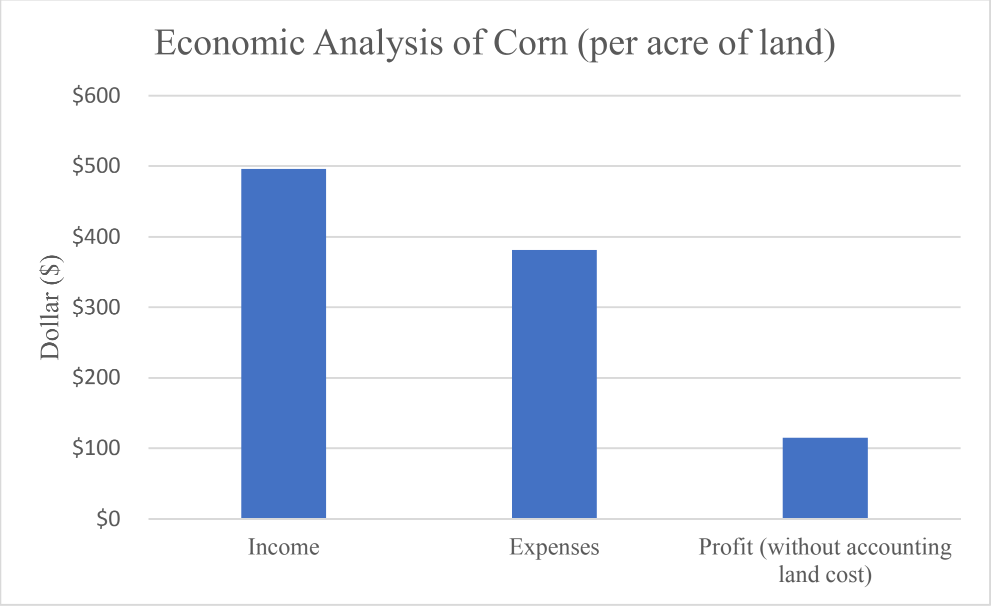


Figure 4-1 Economic Analysis of Corn for an acre of land

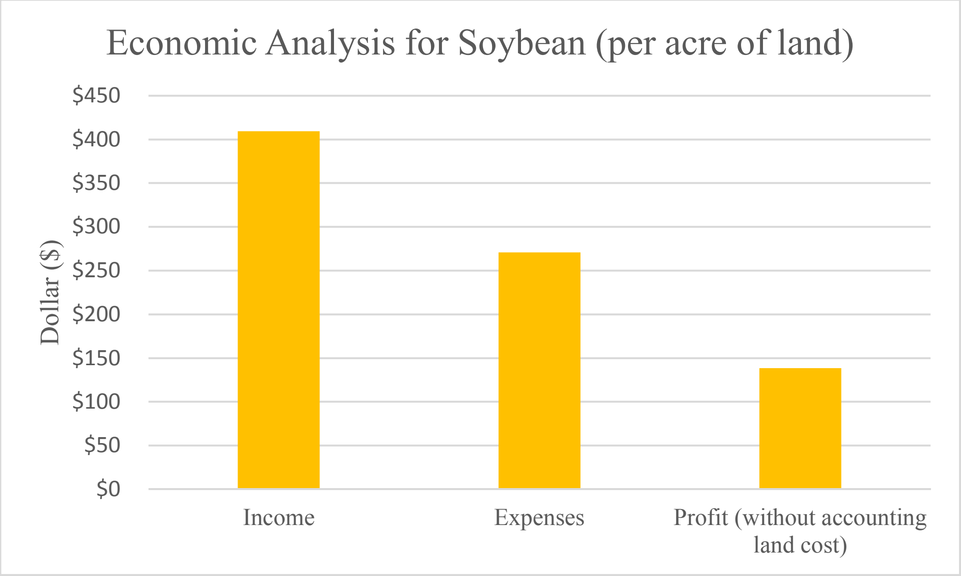


Figure 4-2 Economic Analysis of Soybean for an acre of land

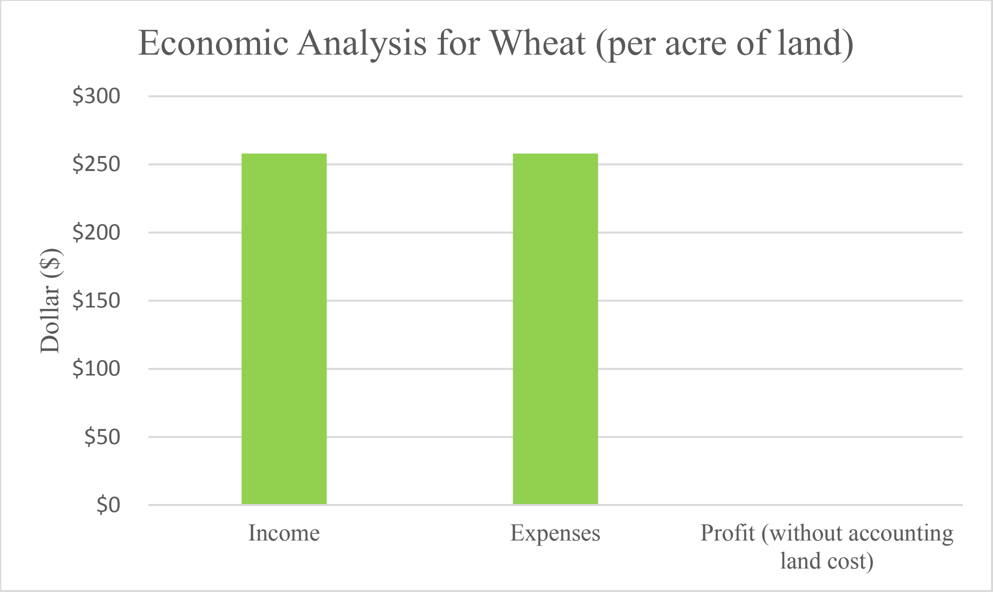


Figure 4-3 Economic Analysis of Wheat for an acre of land

4.2 Environmental assessment of Torrefaction using crop residues (No Allocation)

4.2.1. Results for Corn Stover Torrefaction: SD

The goal of this project is to access the environmental impacts of corn stover grown in SD that can be used to produce torrefied pellets. The corn stover taken for this analysis was 2030 kg. This is the amount of corn stover harvested from an acre of land with a harvest rate of 50%. The LCIA preview results for the CML 2001- Nov. 2010, Global Warming Air (GWP 100 years), including biogenic carbon is shown in table 4-2. CML 2001 is an impact assessment method, which restricts the quantitative modeling to early stages in the cause-effect chain to limit uncertainties. This is based on midpoint categories e.g. climate change, ecotoxicity, etc. [85].

Table 4-2 LCIA preview results for corn stover torrefaction

Processes	**Global Warming Air, including biogenic carbon**
Corn production	-747.7 %
Trucking (5t payload capacity)	7.5%
Diesel mix at refinery	1.1%
Thermal energy from natural gas	91.4%

The table 4-2 shows that the natural gas combustion for the torrefaction has the highest global warming potential while transportation has the lower effect (for the 100km distance from the feedstock producer to the torrefaction facility). But, we can see that the global warming potential from the corn production is negative which implies the greenhouse gases savings eventually.

Figure 4-4 shows the resources consumed and emissions to various compartments by the corn stover torrefaction.

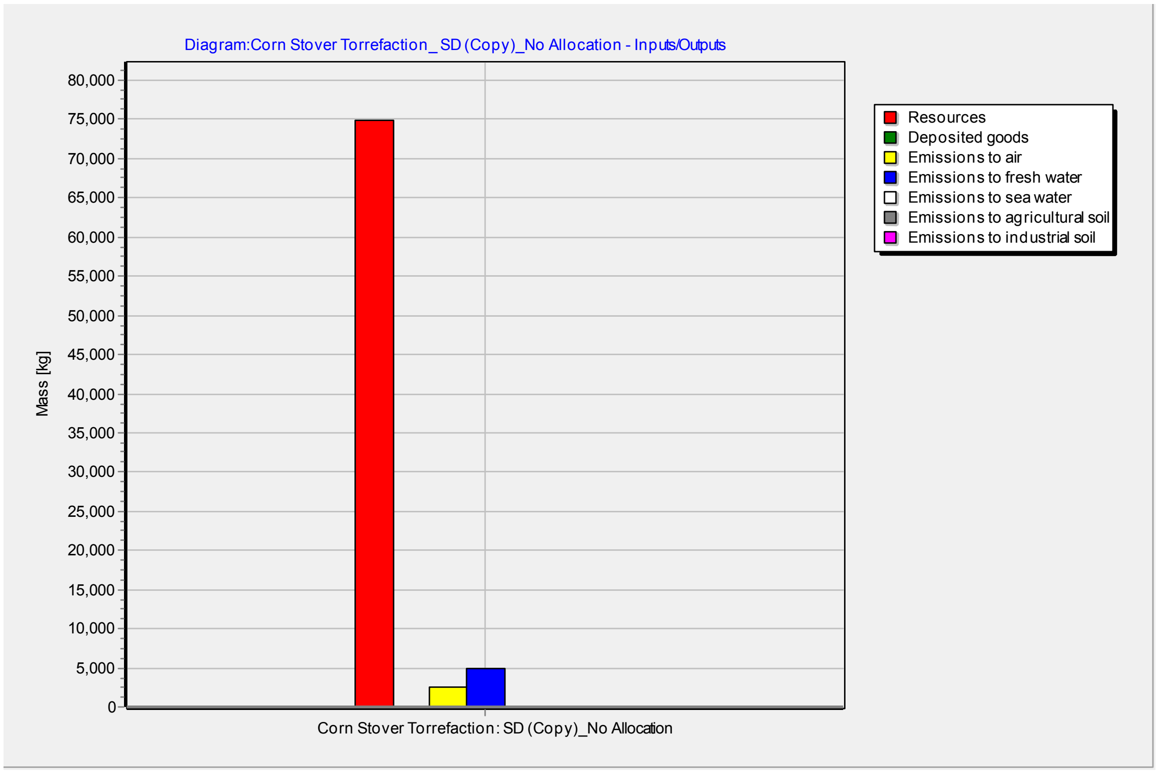


Figure 4-4 Resources consumption and emissions from Corn Stover Torrefaction

The above figure shows that there is higher emission to water bodies than to air. Moreover, the resources consumed (e.g., energy resources and material resources) for this corn stover integrated torrefaction process is higher than the emissions to air, water, and soil.

The resources consumed are higher for the corn production process than torrefaction and transportation process.

Figure 4-5 shows the Global Warming Potential (GWP) graph for the corn stover torrefaction. GWP is expressed in kg of CO_2 equivalent. Similarly, Figure 4-6 and Figure 4-7 show the Acidification Potential (AP) and Eutrophication Potential (EP), respectively. AP and EP are expressed in terms of kg of H+ moles equivalent and kg of N equivalent.

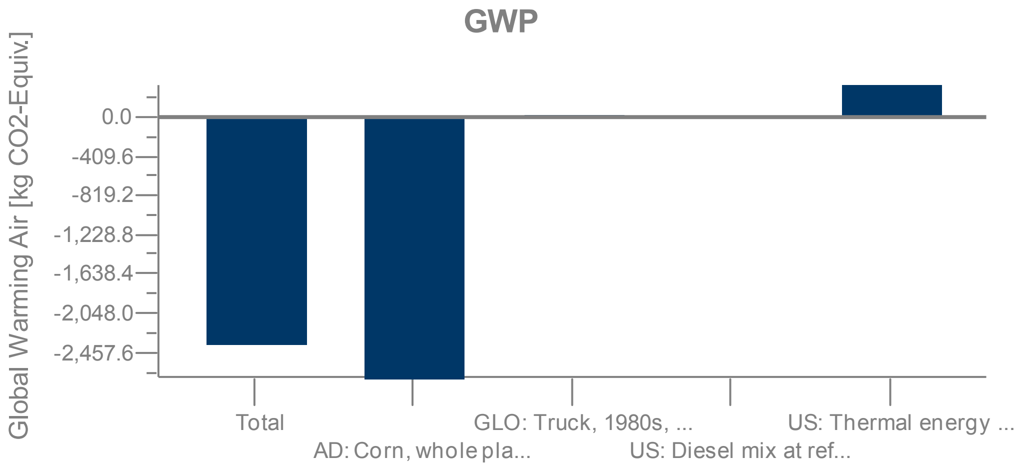


Figure 4-5 Global Warming Potential graph for the corn stover torrefaction

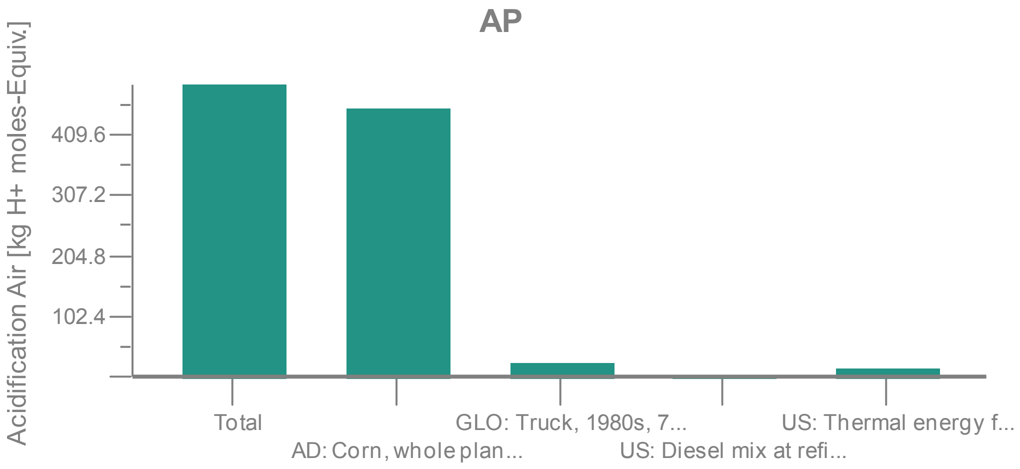


Figure 4-6 Acidification Potential graph for corn stover torrefaction

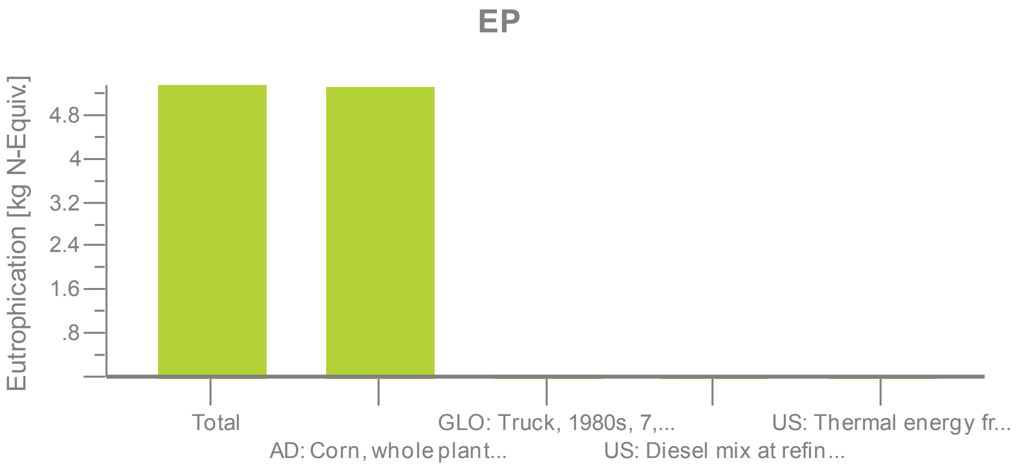


Figure 4-7 Eutrophication Potential from corn stover torrefaction

DB results show that the GWP saving was 2350 kg equivalent of CO2, EP was 5.35 kg N equivalent and AP was 494 kg H+ moles equivalent. Biogenic carbon that the plant takes in during the growth phase factored into the GWP calculation. The total GWP was due to the emissions from transportation and torrefaction process plus the sequestered carbon in the corn. EP graph shows that it has an effect for the corn production only because we use fertilizers during crop production.

4.2.2. Results for Wheat Straw Torrefaction: SD

The feedstocks taken for this study were wheat straw harvested from an acre of land. The mass of wheat straw considered was 1401 kg. This model includes wheat production process followed by transportation of wheat straw and the torrefaction process. These are energy-intensive processes that produce emissions to air, water, and soil. The LCIA preview results for the CML 2001- Nov. 2010, Global Warming Air (GWP 100 years), including biogenic carbon is shown in table 4-3.

Table 4-3 LCIA preview results for wheat straw torrefaction based on CML

Processes	**Global Warming Air, including biogenic carbon**
Wheat production	-542.2 %
Trucking (5t payload capacity)	7.5%
Diesel mix at refinery	1.1%
Thermal energy from natural gas	91.4%

Table 4-3 shows that wheat production has a positive environmental impact since the global warming potential value is negative. Similarly, the thermal energy production from natural gas has significant contribution to the greenhouse emissions in the environment. Figure 4-8 shows the resources and emissions from the wheat straw torrefaction.

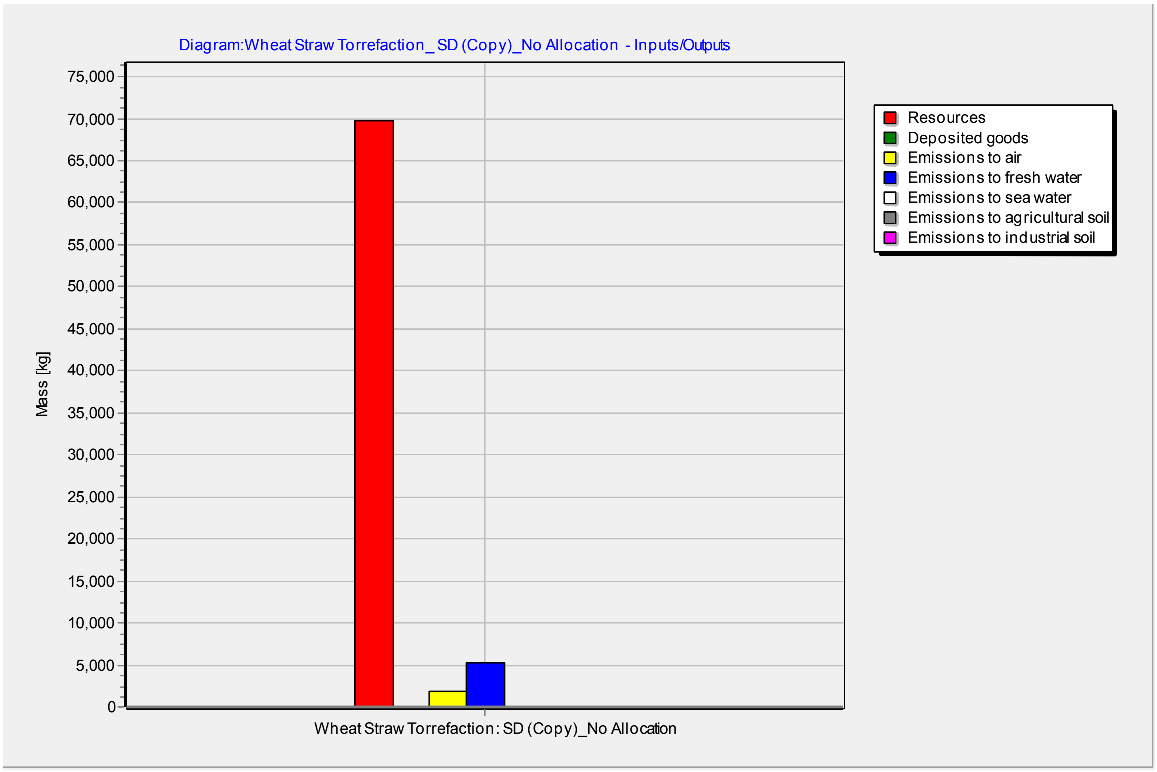


Figure 4-8 Resources and Emissions from wheat straw torrefaction

Similarly, Figure 4-9, Figure 4-10, and Figure 4-11 show the graph for global warming potential, acidification potential and eutrophication potential, respectively.

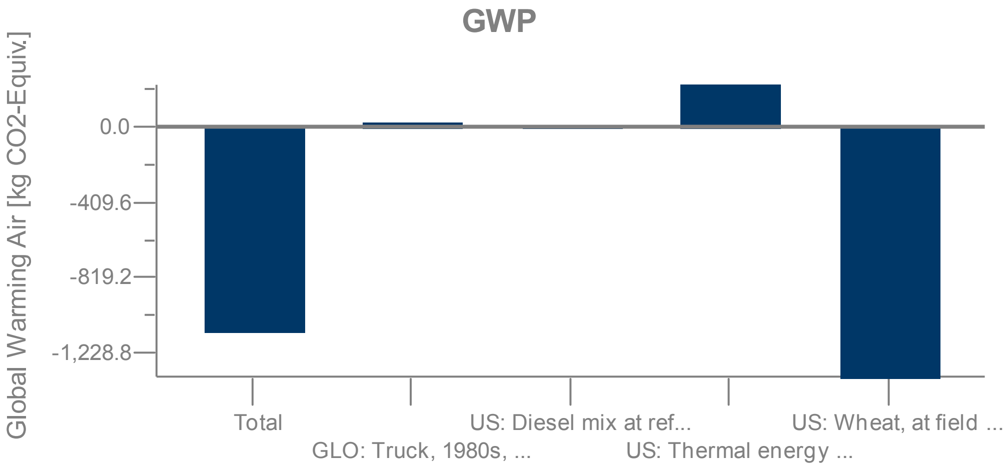


Figure 4-9 GWP form the wheat straw torrefaction

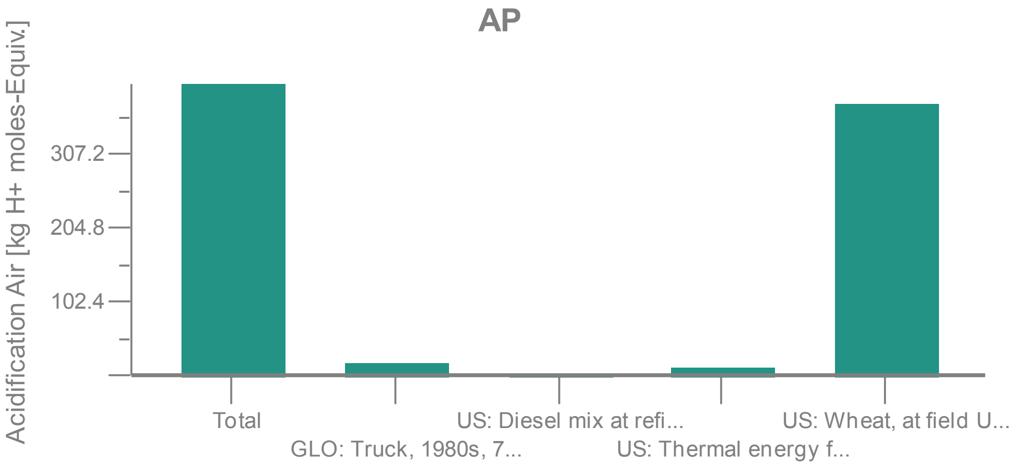


Figure 4-10 AP form wheat straw torrefaction

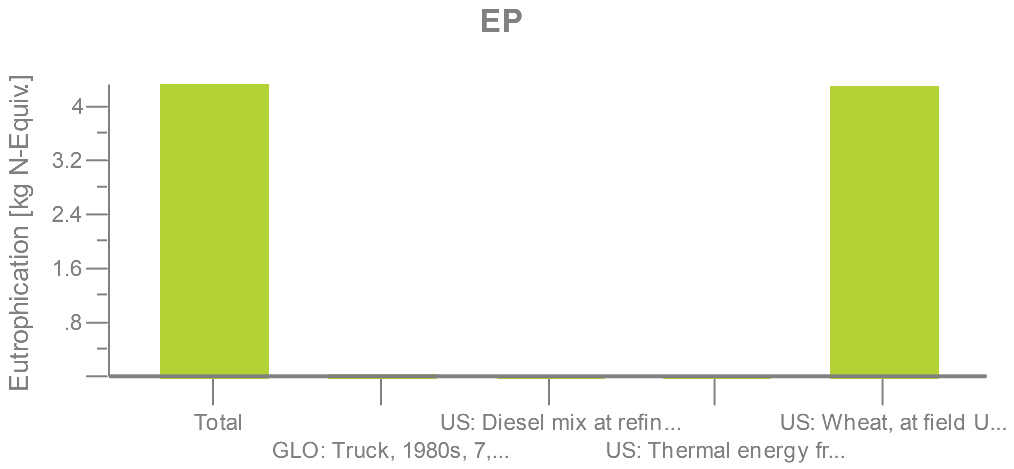


Figure 4-11 EP from wheat straw torrefaction

The LCA results show that global warming potential saving from the wheat straw-based torrefaction was 1100 kg of CO_2 equivalent, eutrophication potential was 4.33 kg N equivalent and AP was 404 kg H+ moles equivalent. GWP results show that wheat requires lot of carbon dioxide for its growth. As per the convention, the effect of GWP due to the biogenic carbon is negative. Although, there are greenhouse gas emissions from the torrefaction and transportation processes, the net GWP is negative. Moreover, the eutrophication effect is only due to the wheat production as shown in Figure 4.8, which is due to the use of fertilizers.

4.2.3. Results for Soybean Residues Torrefaction: SD

The mass of soybean residues taken was 1028 kg. This model also consists of soybean production process followed by the trucking and the torrefaction process. These all are energy-intensive processes that have an effect in the environment. The LCIA preview results for the TRACI 2.1, Global Warming Air, including biogenic carbon is shown in table 4-4.

Table 4-4 LCIA preview results for soybean residues torrefaction

Processes	**Global Warming Air, including biogenic carbon**
Wheat production	-219.6 %
Trucking (5t payload capacity)	7.6%
Diesel mix at refinery	1.1%
Thermal energy from natural gas	91.4%

Figure 4-12 shows the resources consumption and emissions produced from the soybean residues based torrefaction to air, water, and soil.

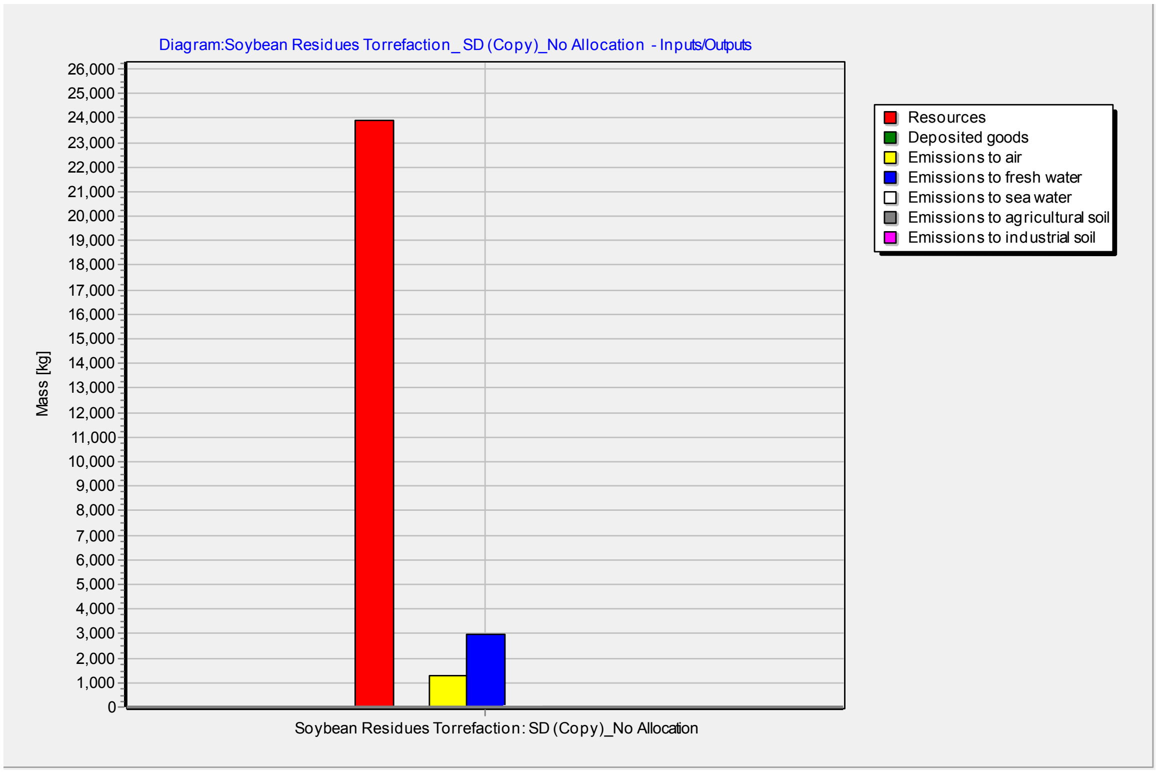


Figure 4-12 Emissions form soybean residues torrefaction

Figure 4-12 shows that there is higher effect on the water bodies than air and soil. This is due to the use of fertilizers and agro-chemicals associated with the soybean production. Similarly, figure 4-13, 4-14, and 4-15 show the global warming potential, acidification potential, and eutrophication potential for soybean residues based torrefaction, respectively.

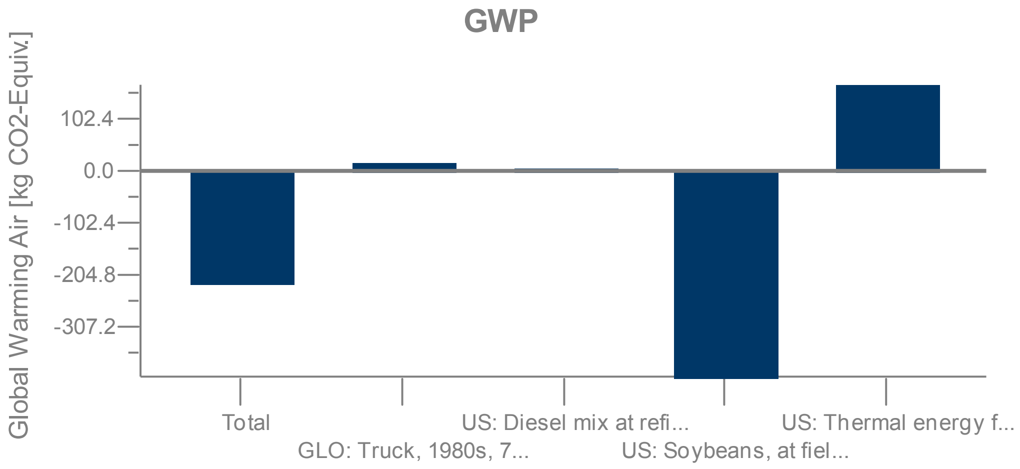


Figure 4-13 GWP for soybean residues based torrefaction

This graph shows that the transportation of soybean residues from the field to the plant has a lower emissions effect than the torrefaction process. However, due to the negative value of GWP for soybean production, the net GWP, which is the sum of GWP from all the processes, is negative.

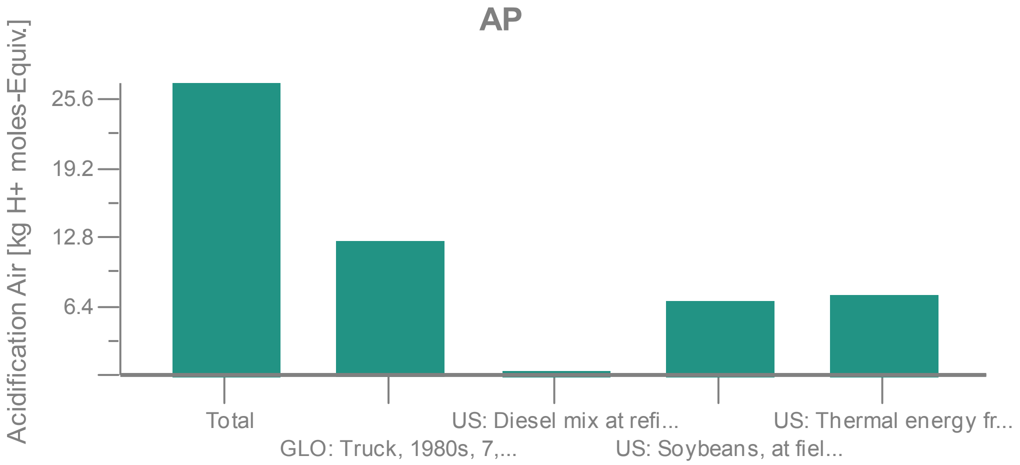


Figure 4-14 AP for soybean residues based torrefaction

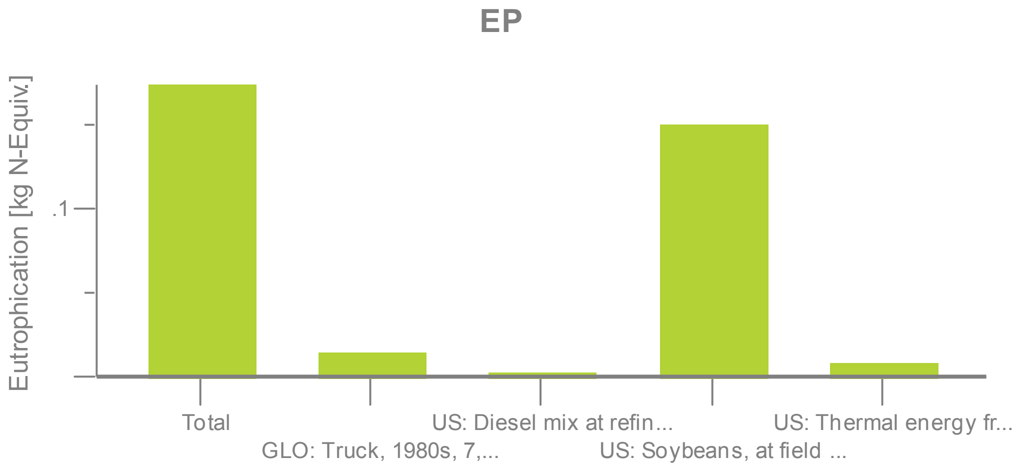


Figure 4-15 EP for soybean residues based torrefaction

The LCA results based on the TRACI impact assessment method shows that the GWP savings for the soybean based torrefaction were 220 kg CO_2 equivalent, the eutrophication potential was 0.174 kg N equivalent and the AP was 27.1 kg H+ moles equivalent.

4.2.4 Environmental effects of crop residues based torrefaction with and without allocation

The allocation method was applied to see the environmental effects of crop residues only. Since, crop residues are the products that are used in the torrefaction industries, allocation helps to consider the environmental burdens of crop residues to crop grains. There is untapped energy in the agricultural residues, which could be transformed torrefied pellets. The functional unit is 1000 kg of crop residues for all the crops (corn, wheat, and soybean). The quantitative results in terms of global warming, acidification, and eutrophication for the crop residues based torrefaction is shown in the table 4-5, with and without consideration of allocation in between grains and residues.

Table 4-5 Effect of allocation for crop residue based torrefaction

Crop residue based torrefaction	Without allocation			Allocation		
	GWP	AP	EP	GWP	AP	EP
Corn stover based torrefaction	-1160	243	2.63	-490	132	1.33
Wheat straw based torrefaction	-791	289	3.09	-369	172	1.76
Soybean residues based torrefaction	-214	26.4	0.17	-87.1	24.2	0.122

4.3 Environmental Assessment of Crop Production

4.3.1 Results for Corn Production

The analysis consisted of three impact categories namely global warming potential, acidification potential, and eutrophication potential. To calculate these impact categories, TRACI impact assessment model was chosen. The functional unit was 1000kg of crop residues. Figure 4-16 shows the resources consumption and emission from the corn production.

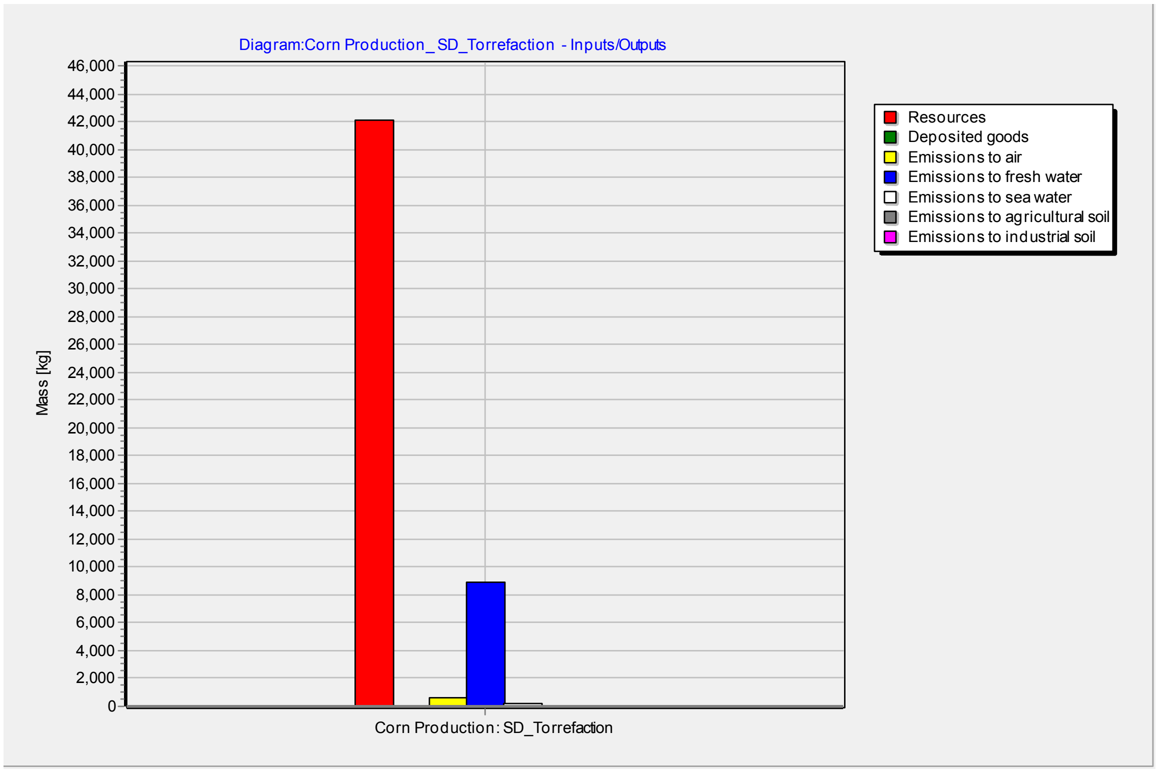


Figure 4-16 Resources and emissions from corn production

Figure 4-16 shows that there are higher emissions to water bodies than to air and soil, which might be due to the use of fertilizers and agro-chemicals during crop production. Figure 4-17, 4-18, and 4-19 show the graph for global warming potential, acidification potential and eutrophication potential, respectively.

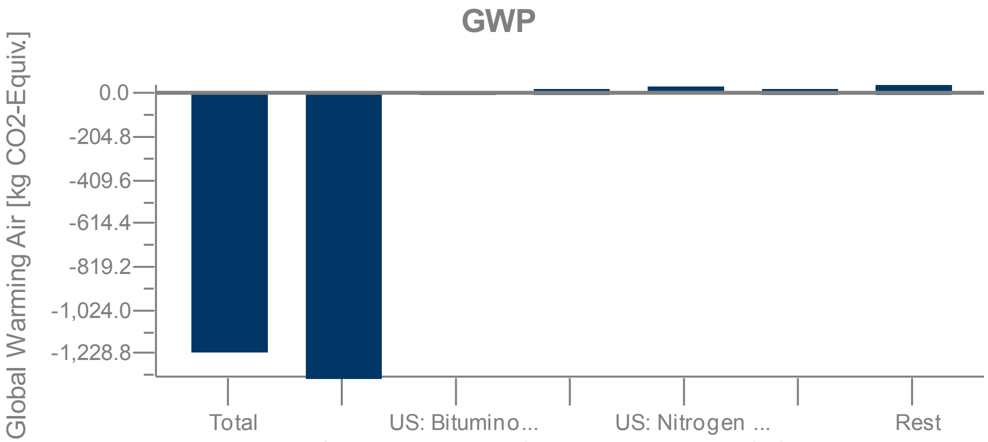


Figure 4-17 GWP for corn production

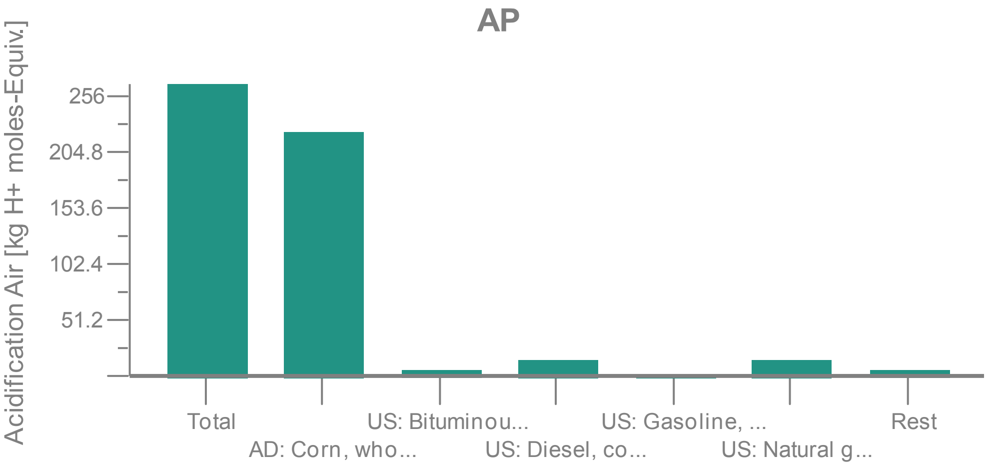


Figure 4-18 AP for corn production

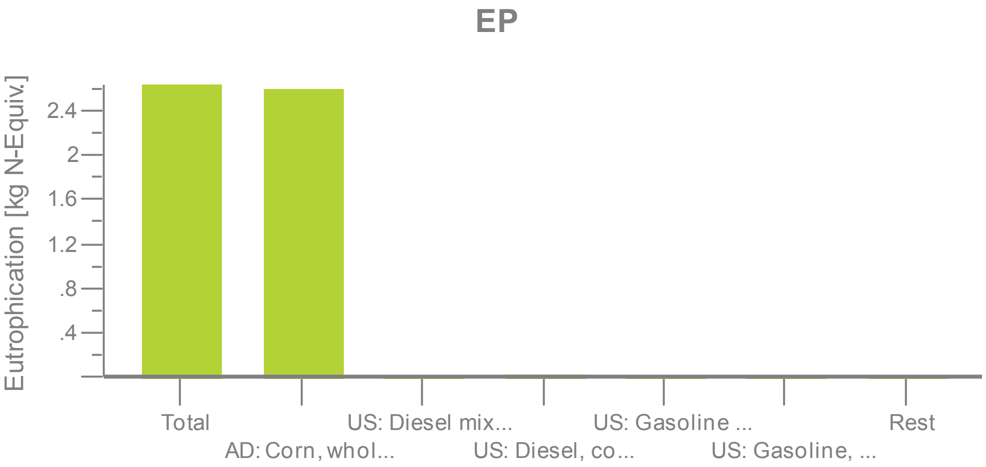


Figure 4-19 EP for corn production

The global warming savings from 1000kg of the corn stover was 1220 kg CO_2 eq. Similarly, the acidification potential for the same 1000kg of the corn stover was 268 H+ moles eq. Moreover, the eutrophication potential was 2.64 kg of N eq.

4.3.2 Results for Wheat Production

The function of the analyzed system is the production of wheat grains and wheat straw. So, the functional unit chosen was 1000kg of wheat straw. TRACI impact assessment provided the LCA analysis, which examined the three impact categories namely global warming potential, acidification potential and eutrophication potential. Figure 4-20 shows the resources consumed and emissions produced from the wheat production process.

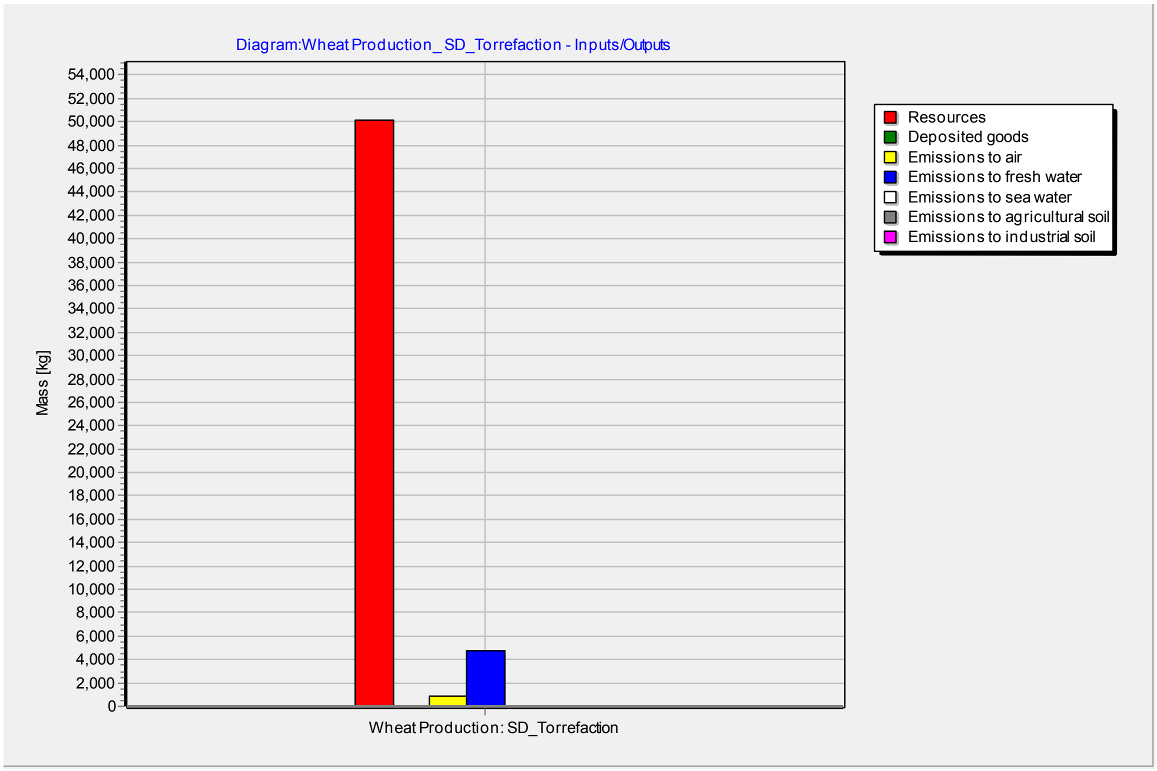


Figure 4-20 Resources and Emissions from wheat production

Similarly, Figures 4-21, 4-22, and 4-23 show the graph for the global warming potential, acidification potential and eutrophication potential.

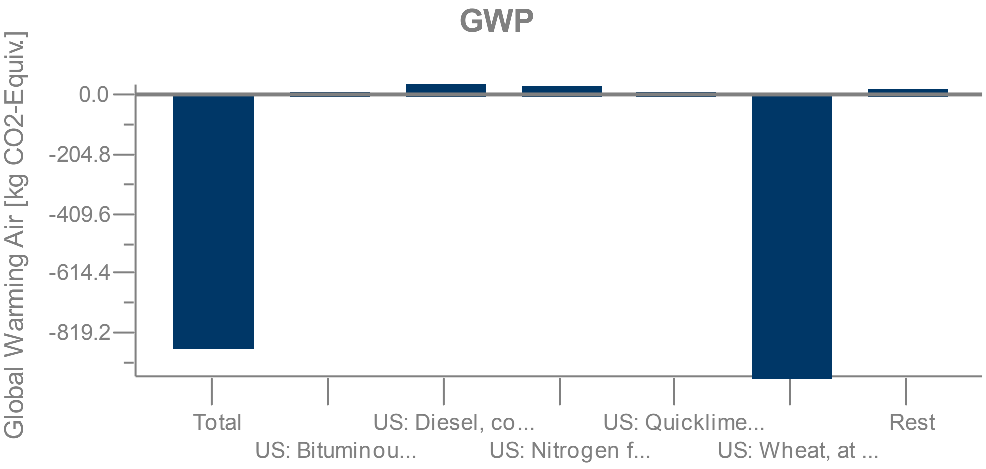


Figure 4-21 GWP for wheat production

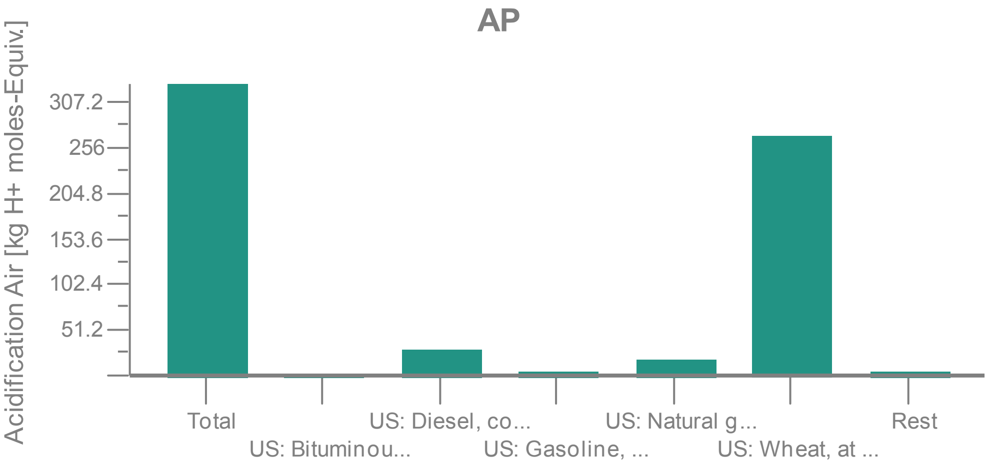


Figure 4-22 AP for wheat production

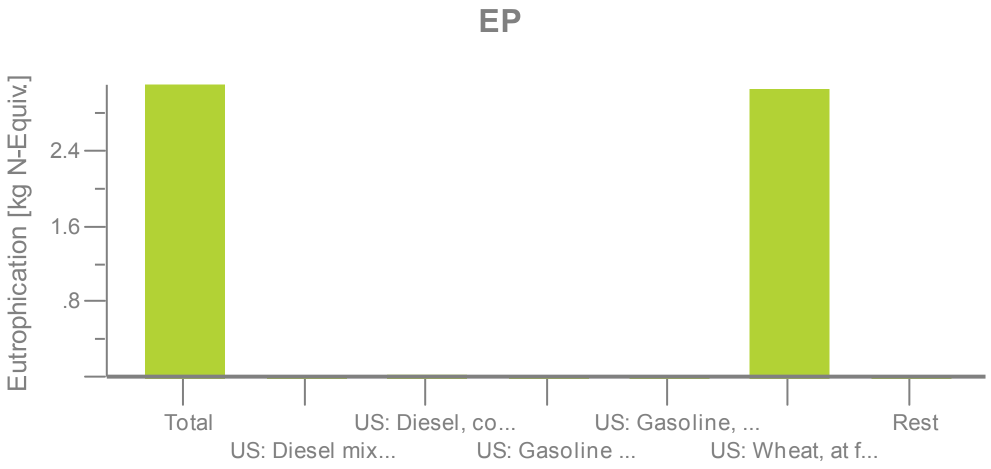


Figure 4-23 EP for wheat production

In case of the wheat production, the global warming saving for a thousand kg of wheat straw was found to be 863 $kg\ co_2\ eq$. The acidification potential of 1000kg of wheat straw was 328 H+ moles eq. Finally, the eutrophication potential for the wheat straw was calculated as 3.11 kg N eq.

4.3.3 Results for Soybean Production

As was the case for corn and wheat productions, TRACI served as the assessment methodology for soybean production. The functional unit was 1000kg of soybean residues. Figure 4-24 shows the resources and emissions associated with soybean production.

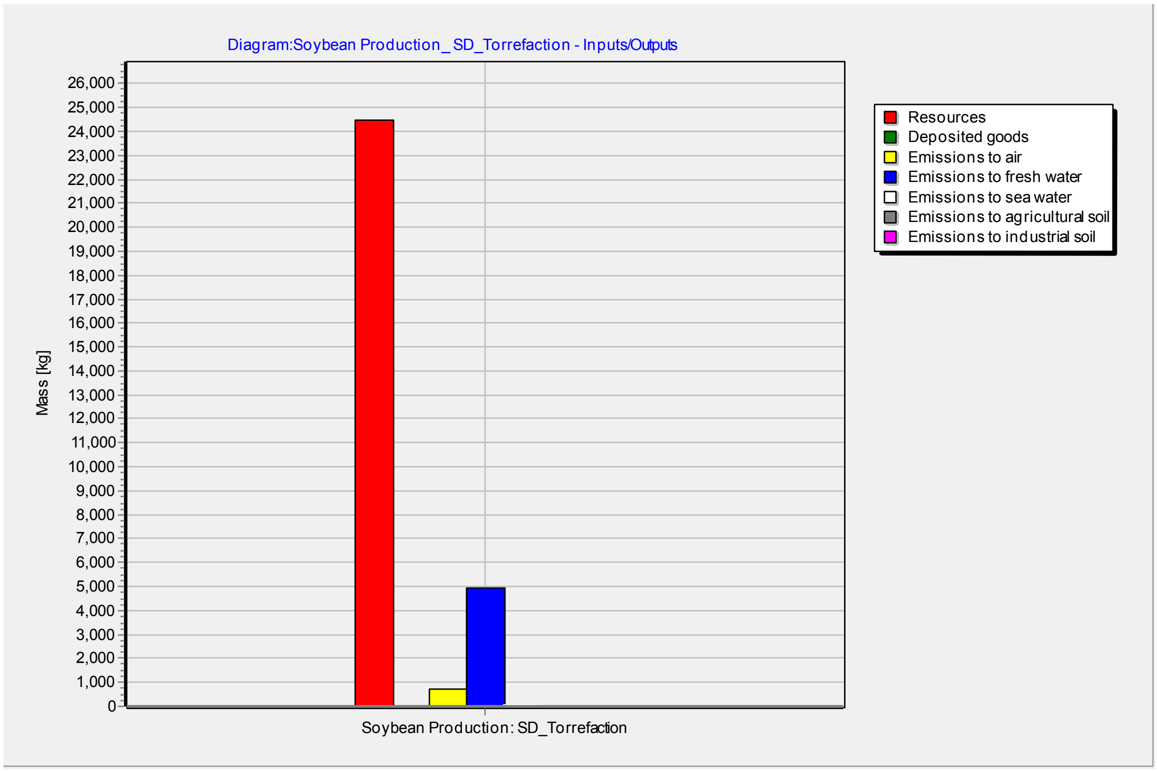


Figure 4-24 Resources and Emissions from soybean production

Figure 4-25, 4-26, and 4-27 show the graph for global warming potential, acidification potential, and eutrophication potential, respectively.

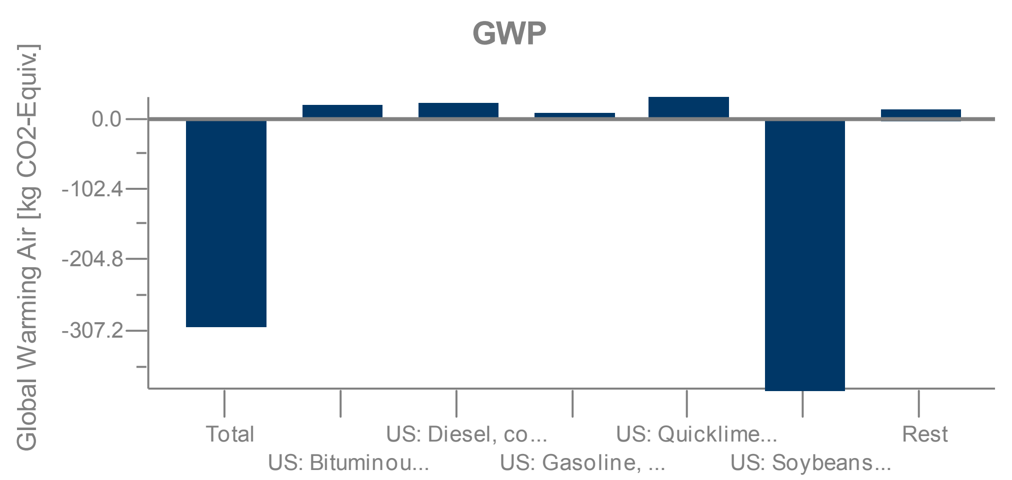


Figure 4-25 GWP for soybean production

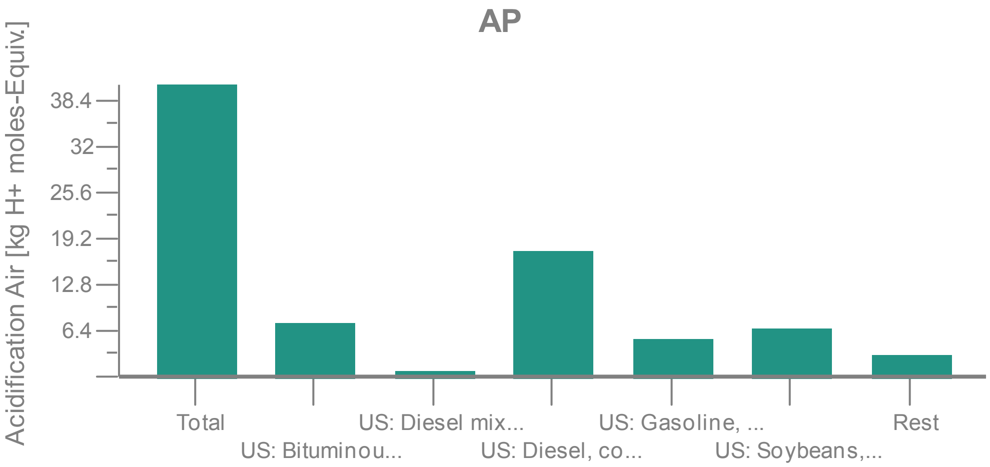


Figure 4-26 AP for soybean production

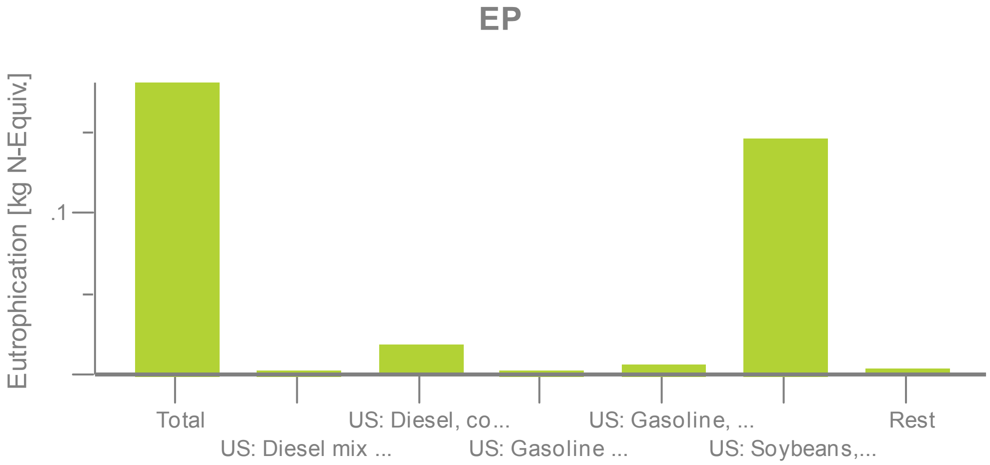


Figure 4-27 EP for soybean production

In the case of 1000kg of soybean residue, the global warming saving was found to be 299 $kgco_2eq$. The acidification potential for this case was 40.5 H+ moles equivalent, whereas eutrophication potential was found to be 0.18 kg N equivalent.

4.4 Environmental assessment for crop rotation

Framers can rotate the crops for their consecutive farming to look for the economic and environmental benefits. There are six combinations for the crop rotation among the corn, wheat, and soybean production. The environmental assessment was performed using the TRACI 2.1 method for global warming potential (GWP), acidification potential

(AP), and eutrophication potential (EP). The functional unit used for the study was the 1000 kg of crop residues (corn stover, wheat straw, and soybean residues). The environmental analysis was done based upon the cumulative effect of all crops rotation by summing up the effect of individual crops' environmental effects, which also shows that the corn-soybean rotation or soybean-soybean rotation is the reliable and reasonable choice for the farmers in terms of environmental benefits. As shown in the table 4-6, the AP and EP values are lower for soybean-soybean rotation and corn-soybean rotation. However, the GWP saving is higher for corn-soybean rotation than the soybean-soybean rotation.

Table 4-6 Environmental assessment of crop rotation (corn, wheat, and soybean)

Crop rotation	GWP (kg CO_2 eq.)	AP (H+ moles eq.)	EP (kg N eq.)
Corn-corn	-2680	448	5.22
Wheat-wheat	-1940	538	6.12
Soybean-soybean	-784	13.32	0.294
Corn-wheat	-2310	493	5.67
Corn-soybean	-1732	230.66	2.757
Wheat-soybean	-1362	275.66	3.207

4.5 Environmental assessment of harvesting crop residues for torrefaction

Table 4-7 shows the environmental results of harvesting corn stover, wheat straw, and soybean residues in terms of GWP, AP and EP. For the 1000 kg of crop residues considered for torrefaction, results show that corn stover has higher global warming saving with respect to wheat straw and soybean residues. However, soybean residue has the least environmental impacts in terms of acidification and eutrophication potential. Thus, table 4-7 gives the implications of harvesting residues for torrefaction.

Table 4-7 Environmental assessment of harvesting residues for torrefaction

Crop residue based torrefaction	Allocation		
	GWP	AP	EP
Corn stover based torrefaction	-490	132	1.33
Wheat straw based torrefaction	-369	172	1.76
Soybean residues based torrefaction	-87.1	24.2	0.122

On comparing the three crops in terms of global warming potential (saving), corn is better than wheat and soybean. This is because the corn absorbs higher amounts of biogenic carbon during its growth phase. The GaBi databases indicates that corn absorbs 1494 kg of carbon dioxide, wheat absorbs 1161.5 kg of carbon dioxide and soybean absorbs 743 kg of carbon dioxide to produce 1000kg of crop residues. The higher amount of corn’s biogenic carbon absorption means corn has a higher negative value of global warming potential. Thus, we can say that corn is more environmentally friendly than wheat and soybean in terms of global warming potential. But in terms of acidification potential, soybean has the lowest value while wheat has the highest potential among three crops. This shows that soybean has the least impact on the environment.

Similarly, on comparing the eutrophication potential, soybean has the least value whereas wheat has the highest value. The eutrophication potential depends on the amount of fertilizer used during the whole plant lifecycle. The amount of nitrogen fertilizer used for 1000kg of corn stover, wheat straw, and soybean residue was found to be 16.9 kg, 21.9 kg, and 0.55 kg, respectively. For soybean, the amount of fertilizer used is the least among the three crops, which results in soybeans having the lowest eutrophication potential. The soybean roots help in nitrogen fixation, thereby reducing the amount of fertilizer used during the soybean lifecycle. The higher use of fertilizer in wheat straw production results in higher eutrophication potential of the wheat straw.

One of the studies performed in the US concludes that the corn stover has a better environmental performance than corn grain as per the global warming potential. This is due to lower consumption of agrochemicals and fuel used in the field operations and lower nitrogen-related emissions from the soil (N_2O, NO_x, NO_3^-) [82]. N_2O emitted from the soil is the dominant greenhouse gas, which is associated with nitrogen fertilizer. Nitrogen losses from soil (NO_x and NO_3^-), also associated with nitrogen fertilizer, are the primary acidification and eutrophication sources. Planting winter cover crops and adapting a no-tillage practice are ways to reduce these nitrogen losses from the soil [82].

The acidification of terrestrial systems is mainly caused by compounds derived from nitrogen (NO_x, NH_3) and sulfur (SO_2 and SO_4), which are common ingredients in fertilizer compounds [86]. Also, nitrate in water bodies is responsible for acidification, eutrophication, and hypoxia that lead to a loss of biodiversity and natural habitats [87].

4.6 Farming practices for corn, wheat, and soybean in South Dakota

In this study, the crop harvest rate for corn stover, wheat straw, and soybean residues are 50%, 66%, and 40% respectively [84]. So, 50% of corn stover, 34% of wheat straw, and 60% of soybean residues will be left in the field. With conservation tillage, it conserves soil moisture, especially traditional drier areas in central and western South

Dakota, improves soil water infiltration, prevents soil erosion, enhances overall soil health, reduces the fuel usage, and consequently lowers the greenhouse gas emissions.

Conservation tillage is a method of soil cultivation that leaves the previous year's crop residue (such as corn stalks or wheat stubble) on fields before and after planting the next crop, to reduce soil erosion and runoff. For this farming practice, at least 30% of the soil surface must be covered with residue after planting the next crop. Some conservation tillage leaves 70% residue or more. Conservation tillage methods include no-till, strip-till, ridge-till and mulch-till [88].This farming practice helps to reduce erosion (water or wind erosion). Even though, most of the soil erosion measures are focused on water erosion, however the Dust Bowl, an ecological disaster of 1930s taught a lesson for the US farmers to adopt farming practices that can help prevent wind erosion as well. The Dust Bowl was a disaster occurred in the Southern Great Plains of North America during the 1930s, when the region experienced extreme wind erosion [89].

For the no-till practice, the soil is left undisturbed from harvest to planting with greater than 30% residue remaining after planting, whereas the mulch tillage disturbs the entire soil surface and is done prior to and/or during planting with greater than 30% residue left after planting [90]. The practice of no-till is being increased from 37% to 45%, from 2004 to 2013, in the South Dakota planted cropland. Moreover, no-till practice appears to go hand-in-hand with diverse crop rotations [90].

4.7 Life cycle assessment: Validation

The results of the LCA study depends on various parameters: model setup, assumptions, system boundaries, functional unit, allocation procedure, impact assessment methods, etc. In addition, the agricultural LCA study varies with the geographical location and the time chosen. In this regard, it is a challenging task to confirm the LCA results. Even so, the values and takeaways messages shared by LCA study have a greater impact to the concerned stakeholders if it is validated. Validation is defined as “the process of ascertaining that the model mimics the real system by comparing the behavior of the model to that of the real system in which the system can be observed and altering the model to improve its ability to represent the real system" [91].

The LCA model should reflect reality as good as possible and necessary. So, introducing validation in LCA models offers possibilities for model improvements as well as improvements of the quality of decisions supported by LCA models, namely of a potential still untapped yet.

Chapter 5 Conclusion

This chapter presents the general findings and draws the main conclusion of this study. Also, few recommendations are given for the future studies.

5.1 Conclusion

An LCA study was conducted for three major crops production: corn, wheat, and soybeans. Two scenarios were focused while creating the LCA models. The first case analyzes the environmental impacts of crop production based on the amount of crop residues. The second case assess the 'cradle-to-gate' system boundary from the acquisition of crop residues to the production of torrefied pellets.

Results show that the environmental performance of crop grains and residues depend on the inputs that were used for the crop production. The inputs that were taken into consideration for the crop LCA modeling were electricity, fuel, water usage, transport, quicklime, fertilizers, agrochemicals, etc. Since corn absorbs larger amount of biogenic carbon during its growth phase, it shows larger greenhouse gases saving than wheat and soybean. Similarly, wheat has more environmental impact in terms of acidification and eutrophication potential. This is due to the higher nitrogen fertilizer application rate which also affects the environmental performance of these three crops. Nitrogen fertilizer accounts about 20% of the global warming potential (including biogenic carbon) for corn, 30% for wheat and 1% for soybean.

The LCA results that were obtained for the crop residues to torrefied pellets process describes the estimate of energy and mass flow and other potential environmental impacts. So, while integrating the torrefaction facility, LCA model shows that the transportation has a minimal contribution for the global warming (for the 100km distance taken from the feedstock producer to the torrefaction facility). But, it is obvious that when the transportation distance increases, the global warming effect also increases proportionately. The thermochemical conversion, torrefaction, shows more environmental impacts than transportation. However, this impact is less in compared with coal. Moreover, this study recommends farmers to follow corn-soybean rotation in SD locality for the torrefaction facility. This conclusion has been drawn based upon the GWP, AP, and EP values of the crop rotation (corn, wheat, and soybean).

The economic analysis of corn, wheat, and soybean was also performed for medium production range in an acre of land. The location selected was Central and East South Dakota, Brookings. Various agricultural expenses like seed, fertilizer, pesticides, operating interest, machinery expenses, drying, etc. were considered for the study. The results show that, soybean has the highest profitability than corn and wheat. For an acre of land with 160 bushels, 45 bushels, and 60 bushels of corn, soybean, and wheat production, the farmers gain a profit of $115, $138.50, and $0 respectively. It shows that farmers have to minimize the agricultural costs in order to have the profit with wheat production (farmers can switch to no-till farming practice). But, while accounting the land cost ($193 for an acre of land in Central & East South Dakota), farmers bear losses of $78, $54.50, and $193 for the corn, soybean, and wheat production respectively. However, farmers can generate extra revenue by selling the crop residues to the nearby biofuel facility or torrefaction plant.

This study also shows that, when done responsibly, residue based torrefaction reduce dependence on coal. So, using torrefied pellets over coal has various advantages like reduction in air and water pollution, recycling of atmospheric carbon dioxide, and displacement of fossil fuel. One of the significant findings from this LCA study (based on mass allocation) is that crop residues are beneficial to crop grains in terms of global warming potential but have higher environmental emissions in terms of acidification and eutrophication potential . This conclusion was drawn based on GWP, AP, EP, and fossil energy usage. To sum up, the LCA results support decision makers in the choice of crop residues for torrefaction.

5.2 Recommendations

The recommendations for the future studies are listed below:

1. It is recommended to account the effects of land use changes in the agricultural LCA.
2. The use phase and end of life of torrefied pellets can be taken into account so as to develop the 'cradle-to-grave' system boundary.
3. The cost of field residues was not considered due to the lack of data for all the crops. So, further studies can be done for the economic analysis of corn stover, wheat straw, and soybean residues, which finally can generate revenues for the farmers.

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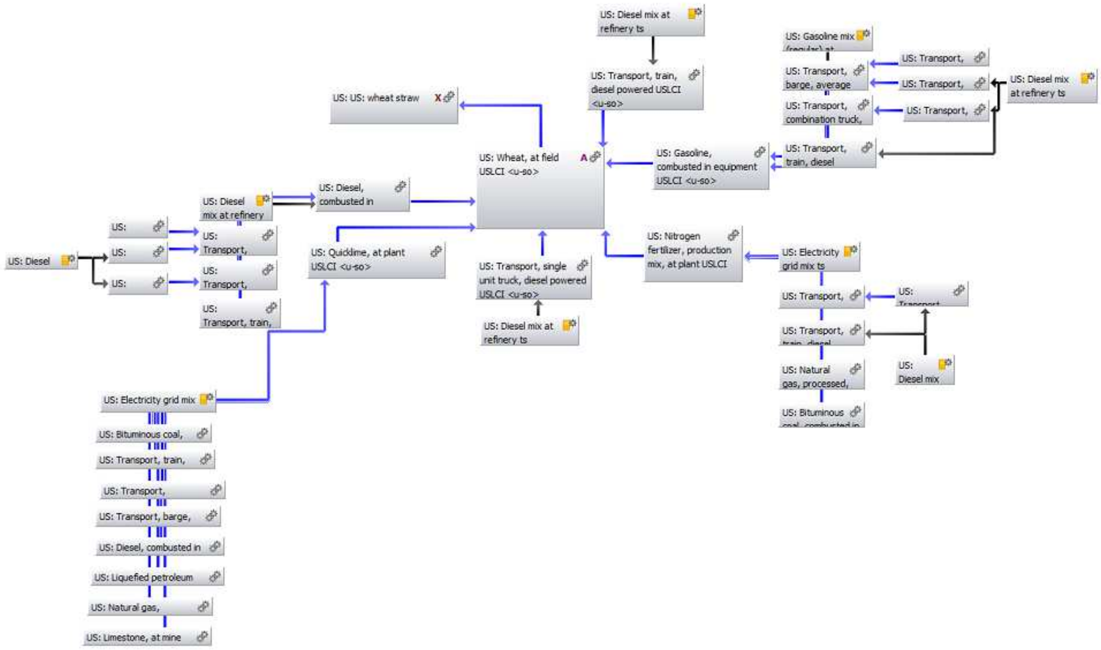
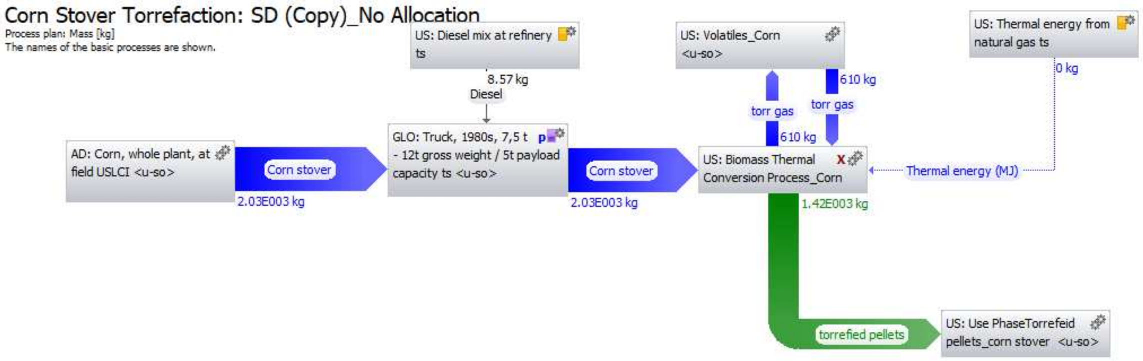
Appendices

Appendix 1: Wheat production modeling in GaBi LCA software



Appendix 2: Corn stover torrefaction (No Allocation)



Appendix 3: Corn stover torrefaction (Allocation)