Assessing the Sustainability of Wheat Straw from the Perspectives of Supply Chain, Waste Disposal and Emissions Reduction

by

HARIKISHORE SHANMUGAM

Department of Bioresource Engineering

McGill University, Montreal

April 2024

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Master of Science

Master of Science

In

Bioresource Engineering

ABSTRACT

Master of Science Harikishore Shanmugam **Bioresource Engineering**

In the realm of agriculture, Canada boasts a flourishing industry accompanied by a substantial volume of agricultural biomass residues. This biomass, originating from the organic matter of living or recently lived organisms, wields a profound influence on the environment. The environmental effects of biomass leftovers include their potential contributions to sustainable energy practices, improvement of soil fertility, and participation in sequestering carbon. The biomass supply chain in Canada entails gathering organic material from the agricultural and forestry resources, converting it to energy, and transferring it to end consumers via various intermediaries. Some agricultural biomass wastes have already been processed to produce energy, while a certain amount of biomass residues is still left on land. The Canadian government and several organizations are putting plans into action to enhance the energy recovery from biomass, such as turning it into biofuels or utilizing it to generate heat and power. These initiatives have the potential to significantly utilize biomass lower greenhouse gas emissions and propel the transition towards a circular and sustainable economy. When compared to other crops, wheat is one the main crop in Canada that generates the most leftovers since it is the major crop cultivated in Canada. Wheat accounts for 45% of the entire crop residue produced annually (28 million dry tonnes), with corn coming in second with 18% (11 million dry tonnes). Thus, the assessment of the wheat residue is more important. In Quebec, nearly 24,557 thousand tonnes of total wheat is produced which leads to 24.557 thousand tonnes of wheat straw production.

This study aims to evaluate the sustainability of wheat straw, a type of agricultural biomass crop residue, focusing on supply chain, waste management, and emission reduction.

The different plans for agriculture biomass waste management were considered while considering the environment and sustainability. The characteristics of biomass waste, the techniques of biomass waste disposal such as anaerobic digestion, composting, gasification, and pyrolysis, environmental and economic benefits were evaluated. Life Cycle Assessment (LCA) has been done in this study with respect to the crop residue (wheat straw) using SimaPro 9 software. The biomass waste management plans are discussed considering the economic viability and environmental standards. The transportation distance of 100 km between the harvest location and the facility and the quantity of 1000 kg of wheat straw are the two common considerations for all four methodologies in the inventory assessments.

According to the IPCC 2013 GWP 100a Method, anaerobic digestion was found to be the best among all with global warming potential percentage of 17.5% while gasification tends to be the poor technique with 38.1%. The social aspect analysis is conducted to determine the percentage of damage assessment concerning four metrics. After conducting a social aspect analysis involving all four methods and evaluating damage percentages about water access, biodiversity, human health, and abiotic resources, the study turns its attention to the supply chain network of the process of anaerobic digestion of wheat straw into biogas. The analysis examined two different strategies: (i) the conventional gasoline truck and (ii) the electric truck, both of which are assessed for a set transit route of 100 kilometers. Then the consumption costs and overall operating costs are calculated for both the trucks. Compared to the commercial vehicle, which has a higher rate of $227.5, the electric truck has a lower consumption rate of $96.5. Furthermore, the electric truck has overall operating costs of $611, compared to the commercial truck with $743.

The noteworthy study examines the kg CO_2 emissions throughout a range of transportation distances, including 25 km, 50 km, 75 km, and 100 km. It finds that a drop of around 36% in kg CO_2 equivalent emissions occurs when the distance is reduced from 100 km to 25 km. These findings offer valuable insights for devising effective strategies to enhance the sustainability of agricultural biomass residues.

RÉSUMÉ

Master of Science Harikishore Shanmugam **Génie des Bioressources**

Dans le domaine de l'agriculture, le Canada possède une industrie florissante accompagnée d'un volume important de résidus de biomasse agricole. Cette biomasse, issue de la matière organique d'organismes vivants ou ayant vécu, exerce une influence profonde sur l'environnement. Les effets environnementaux des résidus de biomasse comprennent leur contribution potentielle aux pratiques énergétiques durables, l'amélioration de la fertilité des sols et la participation à la séquestration du carbone. Au Canada, la chaîne d'approvisionnement en biomasse consiste à collecter des matières organiques à partir des ressources agricoles et forestières, à les convertir en énergie et à les transférer aux consommateurs finaux par le biais de divers intermédiaires. Certains résidus de biomasse agricole ont déjà été traités pour produire de l'énergie, tandis qu'une certaine quantité de biomasse est encore laissée sur les terres. Le gouvernement canadien et plusieurs organisations mettent en œuvre des plans visant à améliorer la récupération de l'énergie de la biomasse, par exemple en la transformant en biocarburants ou en l'utilisant pour produire de la chaleur et de l'électricité. Ces initiatives ont le potentiel d'utiliser la biomasse de manière significative, de réduire les émissions de gaz à effet de serre et de favoriser la transition vers une économie circulaire et durable. Par rapport aux autres cultures, le blé est la principale culture au Canada qui génère le plus de résidus puisqu'il s'agit de la principale culture au Canada. Le blé représente 45 % de l'ensemble des résidus de culture produits annuellement (28 millions de tonnes sèches), le maïs arrivant en deuxième position avec 18 % (11 millions de tonnes sèches). Au Québec, 24,557 mille tonnes de blé a été produit, ce qui entraîne une production de 24,557 mille tonnes de paille de blé.

Cette étude vise à évaluer la durabilité de la paille de blé (résidus de cultures de biomasse agricole) en tenant compte de la chaîne d'approvisionnement, de la gestion des

déchets et de la réduction des émissions. Les différents plans de gestion de la biomasse agricole ont été examinés en tenant compte de l'environnement et de la durabilité. Les caractéristiques des déchets de biomasse, les techniques d'élimination des déchets de biomasse telles que la digestion anaérobie, le compostage, la gazéification et la pyrolyse, ainsi que les avantages environnementaux et économiques ont été évalués. L'analyse du cycle de vie (ACV) a été réalisée sur les résidus de culture de blé (paille de blé) à l'aide du logiciel SimaPro 9. Les plans de gestion de la biomasse sont examinés en tenant compte de la viabilité économique et des normes environnementales. La distance de transport de 100 km entre le lieu de récolte et l'installation et la quantité de 1000 kg de paille de blé sont les deux considérations communes aux quatre méthodologies dans les évaluations d'inventaire.

Selon la méthode GWP 100a du GIEC de 2013, la digestion anaérobie s'est avérée être la meilleure de toutes avec un pourcentage de potentiel de réchauffement global de 17,5%, tandis que la gazéification tend à être la technique la plus médiocre avec 38,1%. L'analyse de l'aspect social est menée pour déterminer le pourcentage d'évaluation des dommages concernant quatre paramètres. Après avoir effectué une analyse de l'aspect social impliquant les quatre méthodes et évalué les pourcentages de dommages concernant l'accès à l'eau, la biodiversité, la santé humaine et les ressources abiotiques, l'étude s'intéresse au réseau de la chaîne d'approvisionnement du processus de digestion anaérobie de la paille de blé en biogaz. L'analyse a porté sur deux stratégies différentes : (i) le camion à essence conventionnel et (ii) le camion électrique, tous deux évalués pour un itinéraire de transit fixe de 100 kilomètres. Les coûts de consommation et les coûts d'exploitation globaux sont ensuite calculés pour les deux types de camions. Comparé au véhicule commercial, qui a un coût plus élevé de 227,5 dollars, le camion électrique a un coût de consommation plus faible soit de 96,5 dollars. En outre, les coûts d'exploitation globaux du camion électrique s'élèvent à 611 dollars, contre 743 dollars pour le camion commercial.

L'étude examine les émissions de CO_2 en kg sur une série de distances de transport, à savoir 25 km, 50 km, 75 km et 100 km. Elle révèle une baisse d'environ 36 % des émissions d'équivalent CO_2 en kg lorsque la distance est ramenée de 100 km à 25 km. Ces résultats offrent des indications précieuses pour l'élaboration de stratégies efficaces visant à améliorer la durabilité des résidus de biomasse agricole.

Acknowledgement

I would like to express my heartfelt gratitude to Dr. G.S Vijaya Raghavan, my respected supervisor, for his consistent support, inspiration, direction, useful advice, and excellent suggestions about my research endeavours. Dr. Raghavan's compassion and moral support are greatly appreciated. It is with great honour and pleasure that I join his prestigious study group, and I am eternally grateful for this essential collaboration.

I am deeply grateful to my co-supervisor, Dr. Chunjiang An, for his steadfast support and advice throughout the duration of my research. Without his technical competence and engineering talents, my project would not have been completed. I am very grateful to Dr. An for his financial assistance, which was critical in the successful completion of this study. The kindness and help supplied are much appreciated, and I am eternally thankful for the important assistance provided.

I would like to take this opportunity to express my deepest appreciation to my friends and graduate students who played critical roles in the successful completion of my research projects. First and foremost, I want to express my gratitude to Linxiang Lyu for his amazing assistance with the software and research responsibilities; his contributions were greatly appreciated. My gratitude also is directed at Siyuan Zhou for his essential support during the data-gathering procedure. Furthermore, I would like to thank K R Jolvis Pou for his consistent moral support during my study, for which I am sincerely grateful.

Throughout this journey, there have been those whose support and drive has helped me proceed forward, and I would like to express my deepest gratitude to them. Learning alongside all of you has been a fantastic experience, and I wish you all the best as you finish your studies at university. A particular mention goes to Yedhu Jayapalan, Akilan Anbarasu, Vignesh

Dhandapani, and Antony Felix, who have made me feel like part of a family away from home. In addition, I am grateful to all my friends in India for their continuous support.

I am deeply grateful to my parents, Shanmugam P and Vijayabhanu R, whose limitless love, inspiration, and unwavering energy have been a continual source of support despite the hundreds of miles that divide us. Their support has helped shape my academic career. Furthermore, my sincere gratitude goes to my brother, Nithinkarthik S, for his constant affection and determination, which encouraged me to successfully complete my education. His continuous support has been the driving factor behind my success. I am also thankful to my grandparents, Rajagopal K and Kaladevi R, for their unfailing love and support, which provided a solid basis for my scholastic ambitions. In a particular tribute, I want to thank Dr. Rajinikanth R and Dr. Bernard Goyette from Agriculture and Agri Food Canada, for their support throughout the project work. I am deeply grateful for their continued presence for their constant help.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

AD – Anaerobic Digestion

CH_4 – Methane

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

EPS – Environmental Priority Strategies

GHG – Greenhouse Gas

GWP – Global Warming Potential

H_2 – Hydrogen

hr – Hour

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

IoT – Internet of Things

kg – Kilogram

km – Kilometer

kmph – Kilometer Per Hour

kWh – Kilowatt Hour

LCA – Life Cycle Assessment

LCIA – Life Cycle Impact Assessment

LCI – Life Cycle Inventory

MJ – Mega Joule

N_2O – Nitrous Oxide

SETOC – Society of Environmental Toxicology and Chemistry

SWOT – Strengths, Weaknesses, Opportunities, and Threats

UN – United Nations

Contribution of Authors

This thesis is a collaborative effort between primary author Harikishore Shanmugam under the supervisors Dr. Vijaya Raghavan, and Dr. Chunjiang An. With particular attention to these tasks, Harikishore Shanmugam composed chapters and carried out evaluations, data collecting, and research. Dr. Vijaya Raghavan (research supervisor) often gave clear instructions and added insightful comments to help determine the course of the project. Working closely with the primary author to guarantee accuracy and high calibre of the thesis, Dr. Chunjiang An (co-supervisor) actively provided valuable support and guidance throughout the research process.

Chapter 1 Introduction

The term "agriculture waste" describes leftover byproducts and wasted materials from crop cultivation and other agricultural activities. These items include crop leftovers, rejected agricultural products, and useless plant components. The proper management of these commodities is crucial for resource conservation and environmental sustainability. Biomass is the organic material derived from the interaction of carbon dioxide (CO_2) in the air, water, and sunlight through photosynthesis. This intricate process produces carbohydrates, essential compounds that serve as the foundational building blocks of biomass (McKendry, 2002). In the past, given the right circumstances, this biomass and agricultural waste were either burned or spontaneously converted into organic fertiliser. Modern methods, on the other hand, focus on using the biomass that results from agricultural waste to produce energy since they realise much power it can produce (Harshawardhan and Upadhyay, 2017). Global agricultural waste output is projected to rise significantly if emerging nations keep enhancing their farming practises (Obi et al., 2016).

In Canada, the agricultural sector assumes a significant role, contributing approximately 8% to the nation's total greenhouse gas emissions. This underscores the pressing need for the adoption and implementation of sustainable practices within agriculture to effectively address and mitigate its impact on the overall carbon footprint (Environment Canada, 2002). The primary source of our global food production is agriculture, which also generates a significant secondary output in the form of agricultural waste. The term "agricultural crop residue" in this thesis refers especially to the plant matter that remains after crops are grown and harvested in Canada's agricultural sector.

In Canada, one of the major agricultural crop biomass residues is wheat straw. Wheat straw, like any other lingo-cellulosic biomass, is mostly composed of cellulose, hemicellulose, and lignin, with trace amounts of ash and soluble substances known as extractives. Depending on the type of wheat, soil, and climate, the general chemical makeup of wheat straw may vary in percentages (Talebnia et al., 2010). The fibrous, hollow, and dry portion of the wheat plant that was not utilised to produce the main crop, wheat grains, is known as wheat straw. Like other crop leftovers, wheat straw is an important resource that may be used in an ecologically responsible and sustainable way. A highly valuable feedstock for the intended low-carbon substitute for fossil fuels is wheat straw biomass.

1.1 Rationale

(i) **Resource efficiency and conservation are justified:** To reduce resource waste, improve resource conservation, and support sustainable agriculture, agricultural biomass leftovers must be used effectively.

(ii) **Reduced environmental impact:** Assessing the environmental impact of various agricultural biomass residue management practises is essential in reducing greenhouse gas emissions and other pollutants as environmental problems, such as climate change, become more pressing.

(iii) **Overall sustainability:** By addressing the management of agricultural biomass leftovers from several angles, this research intends to contribute to the overarching objective of improving sustainability in agriculture, waste management, and energy generation. This will affect how the environment is impacted, how resources are used, and how economic growth is supported.

1.2 Hypothesis

The specific hypotheses for the work are:

- ✓ The efficiency of wheat straw conversion methods, including anaerobic digestion, composting, gasification, and pyrolysis, varies significantly, with one method demonstrating superior efficiency in terms of energy recovery and resource utilization.
- ✓ The environmental impact assessment of wheat straw conversion techniques, considering factors such as emissions, waste reduction, and resource conservation, will reveal that a specific method is more environmentally sustainable compared to others.
- ✓ A Life Cycle Assessment (LCA) will reveal which conversion process for wheat straw among the evaluated approaches has the lowest overall environmental effect and promotes sustainability.
- ✓ Comparing traditional fuel trucks and electric trucks and analysing transportation aspects within the supply chain will show which one of them will significantly reduce CO_2 equivalent emissions and the overall cost.

1.3 Objectives

The primary objective of the study was to evaluate the sustainability of wheat straw concerning waste disposal methods, the enhancement of the supply chain, and the reduction of emissions. The specific objectives of the research are to:

(i) **Determine the best waste disposal practises for wheat straw:** Investigate different disposal methods, such as composting, anaerobic digestion, pyrolysis, and gasification, to ascertain their effects on the environment and the economy, with the goal of identifying the most sustainable one.

(ii) **Analyse the sustainability and efficiency of wheat straw supply chains:** Analyse the whole supply chain, from the production of biomass residue to its use or disposal, to find potential for improving efficiency, lowering resource use, and minimising the cost associated with it.

1.4 Thesis outline

To achieve the objectives, this thesis has been prepared and structured into chapters. A thorough summary, comprising the main aims, particular targets, and the justification for the research, is given in Chapter 1 of the thesis. Chapter 2 will focus on a thorough literature assessment of pertinent research related to the thesis subject, and this groundwork sets the scene for that chapter.

The thesis presents a thorough synthesis of the literature review in Chapter 2, summarising key ideas put forth by several scholars. The literature review also offers insightful information that helps to shape the study strategy and methodology in later chapters. This thorough synopsis not only improves understanding of the current academic environment but also provides context for the upcoming research technique, which will be further discussed in Chapter 3.

A clear technique is provided in Chapter 3, which includes a SWOT analysis and an overview of the steps needed in turning wheat straw into the intended results. Additionally, a thorough summary of the life cycle evaluation is given in this chapter. Chapter 4 will then go into further details about the debates and outcomes that come from this defined technique, clarifying the realisations and discoveries that were made during the study process.

Hence, the findings in Chapter 4 unequivocally highlight that anaerobic digestion stands out as the most effective process for converting wheat straw into a valuable product, namely biogas. Then the supply chain analysis is conducted for the best technique along with the transportation optimization in delivering the wheat straw from harvest area to processing facility. Chapter 5 will subsequently encapsulate a summary of the research, present conclusions drawn from the study, and put forth future recommendations for researchers in the field.

Chapter 2 Literature review

2.1 Waste Management

Waste management is a complicated phenomenon with a variety of ramifications for the society (Ekvall et al., 2007). Waste management systems span the complete life cycle of solid waste, which includes collection, transportation, methods for recovering resources, treatment, and disposal. They start with the temporary storage of garbage in containers (Ghinea et al., 2014). The potential for energy in the byproducts of Canadian agriculture is enormous, at least in principle. Much attention has been paid to the utilisation of waste biomass as a source of food or chemical raw materials (Timbers et al., 1977).

In recent decades, the efficient management of agricultural wastes has become a major problem, inspiring the development of several innovative techniques. These techniques include the use of biochar, the creation of organic fertilisers by composting, and the elimination of environmental contaminants (El-Ramady et al., 2020). The primary aim of waste laws is to inhibit the production of waste. Strict avoidance, reduction at the source, and product reusing are the three realistic strategies for waste prevention. Because safety is the most essential factor in waste management, it is crucial to remember that waste prevention involves more than just lowering the total quantity of garbage produced. It also includes avoiding dangers and hazards (Joshi, 2020).

The combination of successful political, economic, and legal programmes is one of the primary motivations for improving bio-waste management that has been noted by (Luttenberger, 2020). The promotion of resource efficiency and environmental conservation are made possible by this connection. The management of waste faces challenges due to the growing complexity of waste entering the system and the increasing demand for sustainable solutions. These solutions need to be both affordable and effective, ensuring climate protection and contributing to the establishment of a circular economy (Christensen et al., 2020).

2.2 Agricultural waste

The terms "agricultural waste," "agricultural byproducts," and "co-products" refer to plant or animal wastes that are not (or are not further processed into) food or feed and may even be the cause of extra environmental and financial problems in the farming and primary processing sectors (Gontard et al., 2018). This problem is complicated and has significant effects on the economy, society, and the environment. Despite frequently going unnoticed in the bigger picture of agriculture, it merits our attention owing to its extensive ramifications. Because of the profound effects that agricultural waste has on the environment, the economy, and society, it is of utmost significance. Its importance results from a wide range of causes.

On the environmental front, improper management of agricultural waste can lead to soil erosion, air pollution, and water pollution, endangering ecosystems, and biodiversity. Agricultural biomass residual includes a wide range of organic components that are still present after crop harvests and other agricultural activities. Although it is sometimes overlooked, this agricultural residue has enormous potential to help our society overcome pressing issues including the demand for clean, renewable energy sources, the need to enhance soil health, and the proper disposal of garbage. Sustainable agriculture, renewable energy, and environmental stewardship all revolve around the management and use of agricultural biomass leftover.

Residues from agriculture and agro industries pertain to the non-product outputs arising from the cultivation and processing of raw agricultural products. While these residues may harbour valuable materials, their existing economic values often fall below the apparent costs involved in collecting, transporting, and processing them for beneficial use (Tsai et al., 2001).

In Canada, only the Canadian province of Ontario had access to 22.5 million tonnes of sustainably collected agricultural leftover in 2014, of which 12.78 million tonnes came solely from crop residue (Hewson, 2010). By 2030, Canadian government plans to prohibit using coal as resource for power productions and replace it by renewable energy. Therefore, 90% of the electricity will be generated through clean energy. Meanwhile, 90% of Canada's lingo-cellulosic agricultural residues are generated from the Prairie provinces (Alberta, Saskatchewan, and Manitoba) while these regions have not been able to commercially produce agricultural biomass or developed a clear supply chain for biomass pellets (Wetzel et al., 2006; Zheng and Qiu, 2020).

2.3 Biomass

Biomass is an organic substance that comes from growing plants and is produced, among other things, via the photosynthesis process.

Addressing the imperative to mitigate greenhouse gas emissions and diminish reliance on fossil fuels necessitates a strategic shift towards the expansion of renewable energy sources, aligning with energy mix policy objectives. Biomass emerges as a noteworthy contributor to this transition, offering a sustainable alternative within the renewable energy spectrum (Koua et al., 2022). The organic material left behind after agricultural processes including crop cultivation, animal farming, and forestry is referred to as agricultural biomass residue. It is made up of a variety of plant materials, such as crop wastes, animal dung, straw, husks, stalks, leaves, and other agricultural byproducts.

Large amounts of agricultural waste are presently used in developing nations as either raw materials for the paper industry or as supplies for animal feed. However, as the collection and disposal of these leftovers are growing more challenging and expensive, it is typically left as garbage or is just burnt in the fields, leading to serious environmental issues. To produce a solid, liquid, or gaseous fuel, conversion processes might be physical, biological, chemical, or thermal in nature (Biswas et al., 2017).

When managed properly, the beneficial nutrients included in biomass waste can be used. It has a sizable quantity of organic matter and may be treated to remove pathogens, making it suitable for use as soil fertiliser. For organic matter to get mineralized there must be a delay unlike with artificial fertilisers (Chew et al., 2019).

Biomass has become a prominent primary energy source for both developed and developing countries because to the rising worldwide need for power, which is being fuelled by population increase and economic development in emerging countries. Transesterification has become a prominent approach because of the latent potential in waste materials to meet future power demands. It offers high conversion efficiency, is cost-effective, and is useful for industrial applications. To solve urgent energy concerns on a worldwide scale, Shafie et al., 2012 explores the function of transesterification as a key instrument for sustainable energy generation from biomass resources. Canada is a global leader in producing bioenergy from biomass.

A substantial amount of the yearly biomass residue output is made up of agricultural wastes, which are an essential source of energy for both domestic and commercial purposes. The leftovers from crops including rice, wheat, sugar cane, maize, soybeans, and groundnuts are notable examples. The promotion of ecologically responsible farming practises, the reduction of trash, and the creation of sustainable energy all depend on these leftovers, which also support a circular economy and lower greenhouse gas emissions (Koopmans and Koppejan, 1997).

2.4 Agricultural biomass residue

Biomass residual in agriculture refers to the organic components that are still present after agricultural processes, such as harvesting and processing crops, have finished. The plant pieces that make up these remnants include stalks, leaves, husks, shells, and stems. The cultivation and processing of crops including rice, wheat, maize, sugarcane, soybeans, and others often results in their production. Agricultural biomass wastes are interesting because they may be utilised for a variety of things, such as making bioenergy, animal feed, compost, or as a starting point for bioproducts. Effective management is necessary to maximise these leftovers' advantages while reducing waste and their negative effects on the environment. To maximise their potential benefits and minimise negative environmental consequences, these relics must be managed properly.

A huge quantity of agricultural biomass leftovers is produced in Canada's thriving agricultural sector. In the production of bioenergy from biomass, Canada is a world leader.

2.5 Agricultural biomass crop residue

The link between agricultural biomass crop residue and biomass residue is based on the fact that agricultural biomass crop residue is a subset of biomass residue. Biomass residue is a more general term that encompasses a wider variety of organic materials from different sources with diverse applications, including energy production and industrial use. Agricultural biomass crop residue, on the other hand, primarily originates from agricultural activities and has specific applications in agriculture.

Globally, the amount of residue removed by grazing cattle varies according to variables including agricultural productivity, current weather patterns, and farmer's income. Furthermore, factors such as the size of the land, the ownership of animals, and the labour force availability impact crop productivity and residue disposal practices (Rakkar and Blanco-Canqui, 2018).

Canada produces 82.4 million dry tonnes of agricultural leftovers annually on average. The results show that the production of agricultural residue is dominated by wheat straw (Li et al., 2012). The average available crop residues removed from land in Canada from 2001 to 2010 of various crop residues shown that wheat has the highest percentage than any other crop residues.

Table 2.1 The average available crop residues removed from land in Canada from 2001 to 2010

Type of crop	**Average available crop residues removed from land in Canada (Million dry tonnes per year)**
Wheat	28
Corn	11
Barley	8
Oats	5
Canola	4
Soybeans	3
Dry peas	2
Flaxseed	1

Table 2.1 provides a detailed summary of the average amount of agricultural residues removed from Canadian land between 2001 and 2010. This data contributes crucial information to our knowledge of land practices and resource dynamics in Canada by offering insightful

information about the management and use of agricultural biomass throughout the past decade. From the **Table 2.1**, Wheat produces the maximum average available crop residues removed from land in Canada with 28 million dry tonnes per year which is followed by Corn with 11 million dry tonnes per year.

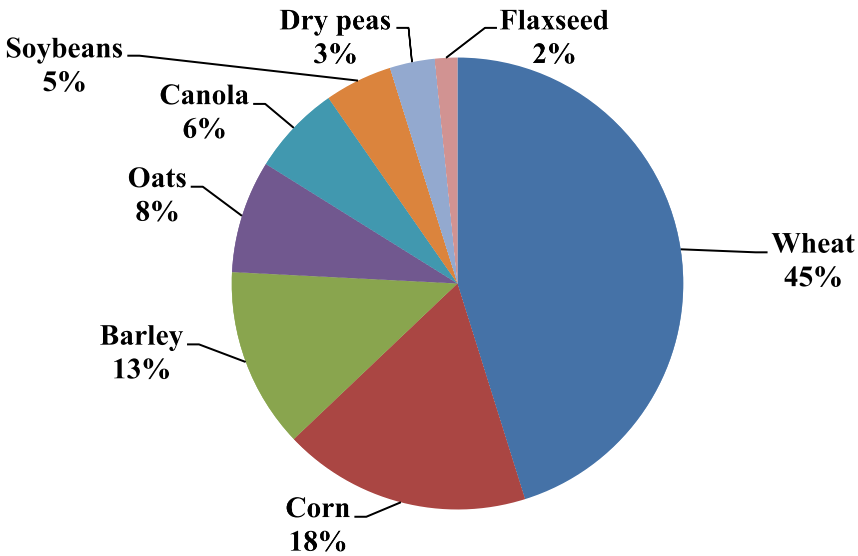

Figure 2.1. Percentage of average available crop residues removed from land in Canada

The average proportion of agricultural wastes removed from Canadian land is shown in **Figure 2.1.** From the graph, wheat straw which is the residue from wheat has the highest percentage of average available crop residues removed from land in Canada during 2001-2010 of nearly 45% followed by Corn at 18%. From the findings, it is very important to analyse the life cycle assessment for wheat straw to determine its sustainability.

2.6 Wheat

Wheat is the cereal that is farmed on the largest scale in the world and is a major food and nutritional protein source for people all over the world. When raw flour is ingested or breathed in, wheat proteins may have negative effects (Battais et al., 2008). Approximately 17% of the world's arable land, or more than 200 million hectares, is used for wheat cultivation. It plays a vital function in the human diet as one of the primary sources of calories and protein (Jones, 2005).

Numerous elements, including high-yielding cultivars, pesticides, fertilisers, mechanisation, and other energy inputs, have an impact on wheat output. The agroclimatic zone, energy input, and technological level are the main elements influencing wheat production. All these factors work together to increase wheat output (Singh et al., 2007). The consumption of wheat is directly linked to population growth, as it is a fundamental crop in numerous countries (Ramdas et al., 2012).

2.6.1 Canadian statistics

As per data from Agriculture and Agri-Food Canada (AAFC) and (Statistics Canada, 2023), the statistics for all wheat in Canada for the years 2022-2023, 2023-2024 (forecast) provided various parameters includes area seeded, area harvested, yield, and production is provided in the **Table 2.2**.

Table 2.2 All wheat statistics for Canada according to AAFC December 15, 2023

Parameters	2022-2023	2023-2024*	Percentage difference (%)
Area seeded (thousand hectares)	10,274	10,938	6.47
Area harvested (thousand hectares)	10,082	10,682	5.95
Yield (tonnes per hectare)	3.41	2.99	-12.35
Production (thousand tonnes)	34,335	31,954	-6.94

The symbol "*" represents the forecast for the corresponding year 2024.

According to (Ruiz et al., 2012), nearly 1 kg of wheat straw has been produced for every 1.3 kg of production of wheat grain. To calculate for the year 2023-2024,

(1) Total wheat production

$$\textbf{Total wheat production} = \textbf{Area harvested} \times \textbf{Wheat yield} \quad \textbf{(2.1)}$$

$$= 10{,}682 \times 2.99$$

$$= 31{,}934.18 \text{ thousand tonnes.}$$

(2) Straw to grain ratio

$$\textbf{Straw to grain ratio} = \frac{\textbf{Weight of wheat straw}}{\textbf{Weight of wheat grain}} \qquad \textbf{(2.2)}$$

$$= \frac{1}{1.3}$$

= 0.769

(3) Estimated wheat straw production

$$\textbf{Estimated wheat straw production} =$$

$$\textbf{Total wheat production} \times \textbf{Straw to grain ratio} \qquad \textbf{(2.3)}$$

= 31,934.18 × 0.769

= 24,557.38 thousand tonnes.

2.6.2 Provincial (Quebec) statistics

According to Annual Crop Inventory (Government of Canada, 2018), Quebec produces nearly 1% of the wheat in Canada where, Saskatchewan produces 45% of overall wheat in Canada. The calculation of wheat straw follows for 2023-2024:

(1) Total wheat production

$$\textbf{Total wheat production} = \textbf{Area harvested} \times \textbf{Wheat yield} \qquad \textbf{(2.4)}$$

= 10.682 × 2.99

= 31.934 thousand tonnes.

(2) Straw to grain ratio

$$\textbf{Straw to grain ratio} = \frac{\textbf{Weight of wheat straw}}{\textbf{Weight of wheat grain}} \qquad \textbf{(2.5)}$$

$$= \frac{1}{1.3}$$

= 0.769

(3) Estimated wheat straw production

$$\textbf{Estimated wheat straw production} = \textbf{Total wheat production} \times \textbf{Straw to grain ratio} \quad \textbf{(2.6)}$$

$= 31.934 \times 0.769$

$= 24.557$ thousand tonnes.

Table 2.3 Canada level and Provincial (Quebec) level wheat straw production

Parameters	Canada	Quebec
Total wheat production (thousand tonnes)	31,934.18	31.934
Wheat straw production (thousand tonnes)	24,557.38	24.557

A comparative study of wheat straw output at the provincial level (Quebec) and national level (Canada) is presented in **Table 2.3.**

According to (Li et al., 2012), the amount of wheat straw that is been used for the livestock is calculated according to data that was available for the period of 2001-2010. According to this analysis, overall residue output less soil conservation and animal consumption equals agricultural residue availability for ethanol conversion. **Table 2.4** outlines the total amount of crop residue removed and available for biofuel production specifically in Quebec.

Table 2.4 Total crop residue removed and available for biofuel

Province	Total crop residue production (million dry Mg yr^{-1})	Total available residue removed from land (million dry Mg yr^{-1})	Total available residue for biofuel (million dry Mg yr^{-1})
Quebec	5.88	4.46	3.55

The formula for animal bedding or livestock used is determined by:

$$\textbf{Livestock used} = \textbf{Residues removed from land} - \textbf{Residue available for biofuel} \qquad \textbf{(2.7)}$$

$$= 4.46 - 3.55$$

$$= 0.91 \text{ million dry Mg yr}^{-1}$$

The estimated amount of crop residue used for livestock used would be 0.91 million dry Mg yr^{-1}.

$$\textbf{Percentage used for livestock} = \frac{\textbf{Livestock used}}{\textbf{Residue removed from land}} \times \textbf{100} \qquad \textbf{(2.8)}$$

$$= \frac{0.91}{4.46} \times 100$$

$$= 20.45\%$$

For livestock, nearly 20.45% of wheat straw residue is used.

From Table **2.3**, the wheat straw production in Quebec is 24.557 thousand tonnes.

The livestock used is 20.45% and thus the total amount of wheat straw used for livestock is 5.021 tonnes. The remaining 79.55% (19.535 tonnes) of the wheat straw residues can be effectively used for various purposes including the conversion of wheat straw into bioethanol.

2.7 Wheat straw

Wheat straw has a complex link with Canada that includes agriculture, sustainability, economic effect, research, and other areas. Because the nation produces a large amount of wheat, managing and using wheat straw is important for both the agricultural environment and larger sustainability initiatives. For several reasons, the environmental analysis of disposing of wheat straw may be deemed more significant or vital than that of maize stover. One of the most extensively grown cereal crops is wheat, and in certain places, the amount of wheat straw produced can be more than that of maize stover. Effectively handling a greater amount of wheat straw raises serious environmental issues.

Wheat straw processing is essential for sustainable agriculture and resource efficiency because it converts agricultural byproducts into valuable commodities and energy sources. Wheat straw, a renewable biomass feedstock, is used in the processing to produce bioenergy, generate bioproducts, and enrich soil, reducing waste and contributing to a more sustainable bioeconomy. This practice not only reduces reliance on fossil fuels, reduces greenhouse gas emissions from open burning, and improves soil health, but it also expands the uses of wheat straw, promoting a circular economy and bolstering agricultural systems' overall resilience in the face of environmental challenge.

Chapter 3 Methodology

3.1 SWOT analysis

SWOT stands for "Strengths, Weaknesses, Opportunities, and Threats." The purpose of a SWOT analysis is to take the data from the environmental study and divide it into two categories: external (opportunities and threats) and internal (strengths and weaknesses) (Danca, 2005). To evaluate the possibilities and difficulties of using crop leftovers for a variety of reasons, such as the generation of bioenergy, the enhancement of soil health, or other sustainable agricultural practices, a SWOT analysis for agricultural biomass crop residue could prove helpful. In **Table 3.1**, a SWOT analysis is presented, focusing on the strengths, weaknesses, opportunities, and threats associated with wheat straw.

Table 3.1 SWOT analysis of wheat straw

Strengths	Weaknesses	Opportunities	Threats
Renewable resource	Restricted availability	Energy production	Competing uses
Reduced emissions	Transportation challenges	Waste Management	Land use change
Versatility	Nutrient removal	Carbon credits	Regulatory Challenges

3.1.1 Strengths

(1) **Renewable resource**: Wheat straw is produced from leftover crops, leftovers, and residues, making it a renewable resource.

(2) **Reduced emissions**: Less carbon dioxide is released into the atmosphere when using agricultural biomass waste as fuel than when using fossil fuels, which can reduce greenhouse gas emissions.

(3) **Versatility:** There are several uses for wheat straw, such as making paper, bedding animals, and maybe even producing bioenergy.

3.1.2 Weaknesses

(1) **Restricted availability**: The utilisation of agricultural biomass waste as a reliable fuel source may be constrained by its seasonal and crop-dependent availability.

(2) **Transportation challenges**: Access to agricultural biomass waste for various sectors can be challenging due to high transportation costs, particularly for waste produced in remote locations.

(3) **Nutrient removal:** The removal of straw from fields for different purposes might cause the soil to become depleted of nutrients, which would affect crop yields in the future.

3.1.3 Opportunities

(1) **Energy production**: As a substitute for fossil fuels, wheat straw may be utilised to generate energy in the form of heat, electricity, or biogas.

(2) **Waste management**: Using agricultural biomass waste can cut down on the volume of garbage dumped in landfills, offering a sustainable alternative.

(3) **Carbon credits:** The utilisation of agricultural biomass waste can be eligible for carbon credits, giving farmers and companies a second source of income.

3.1.4 Threats

(1) **Competing uses**: Wheat straw is in more demand across a range of sectors, which might result in rivalry for this resource and limit its supply for some uses.

(2) **Land use change**: The use of agricultural biomass waste may result in a shift in land use, which may have detrimental effects on the ecosystem, such as deforestation and the extinction of species.

(3) **Regulatory challenges**: Agricultural biomass waste utilisation can be complicatedly governed by laws and regulations, which can make it difficult for it to be adopted.

3.2 Disposal techniques of wheat straw

Wheat straw, a by-product of wheat harvesting, can be disposed of through various techniques, depending on the desired outcome and environmental considerations. Here are some common disposal techniques for wheat straw.

3.2.1 Four scenarios of wheat straw disposal

In this study, four different techniques are considered for converting the wheat straw into the useful product.

Table 3.2 Different outputs through corresponding processes

Process	**Output**
Anaerobic digestion	Biogas
Pyrolysis	Biochar
Composting	Compost
Gasification	Syngas

The different outputs from the appropriate operations in the conversion of wheat straw are shown in **Table 3.2.** In short, the four techniques of converting the wheat straw are anaerobic digestion, pyrolysis, composting, and gasification which results in the output product as biogas, biochar, compost, and syngas respectively.

3.2.1.1 Converting wheat straw into biogas by anaerobic digestion

For the conversion and treatment of different complex biomass and hazardous wastes, anaerobic digestion (AD) is a biological process that is both ecologically benign and appealing now. Using this process, complex organic matter is broken down by microorganisms in the absence of oxygen, producing "biogas," an energy-rich by-product (Laiq et al., 2019). Anaerobic digestion is a sustainable and ecologically beneficial way of turning wheat straw into biogas.

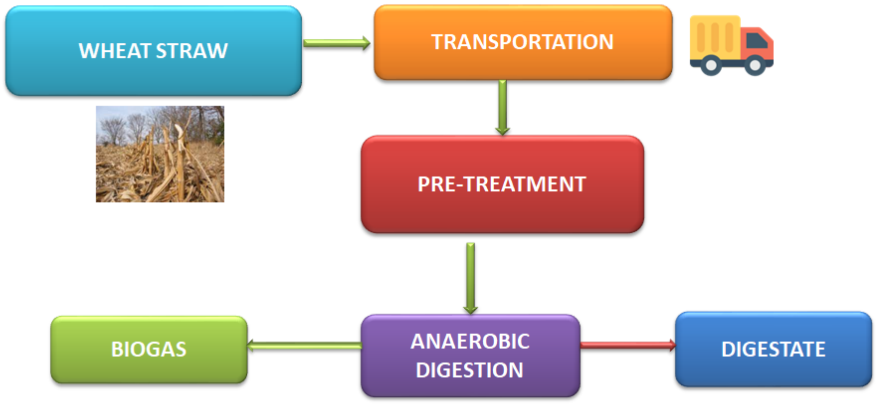

Figure 3.1 Flowchart of converting wheat straw into biogas and by-product digestate by anaerobic digestion

In **Figure 3.1**, a comprehensive flowchart depicts the process of converting wheat straw into biogas and the by-product digestate through anaerobic digestion. This visual representation offers a step-by-step overview of the intricate stages involved in the transformation of wheat straw, providing a clear understanding of the anaerobic digestion process and its outcomes.

(1) Feedstock preparation: The agricultural leftover, wheat straw, is first gathered, cleaned, and cut into smaller pieces. This stage of preparation increases the amount of organic material that microorganisms may reach within the straw.

(2) Collection: To prepare them for additional processing, crop wastes are gathered from the fields or storage areas.

(3) Transportation: The anaerobic digestion facility receives wheat straw for transportation.

(4) Pre-treatment: To increase their digestibility and maximise the anaerobic digestion process, wheat straw may occasionally go through pre-treatment. Size reduction procedures such as chopping and shredding can be used as pre-treatment treatments.

(5) **Setup of the anaerobic digester:** The processed wheat straw is placed into an anaerobic digester, a sealed apparatus made to function without oxygen.

(6) **Anaerobic digestion:** Crop leftovers are fed into anaerobic digesters, where the organic matter is broken down by microorganisms in the absence of oxygen, producing biogas and digestate.

(7) **Biogas and digestate:** The two primary products of anaerobic digestion are digestate, an organic fertiliser high in nutrients, and biogas, which is mostly composed of methane and may be utilised to create electricity.

(8) **Energy:** Biogas may be used to generate heat or electricity for use in buildings, businesses, and other settings.

(9) **Fertiliser:** Digestate is sprayed as an organic fertiliser over fields of crops to supply the nutrients needed for fresh crop development.

(10) **Heat and heating**: Biogas heat may be utilised for space heating as well as other heating applications.

Several variables must be properly controlled and monitored to maximise the generation of biogas and the digestate's quality. This process's ultimate objective is to turn organic waste materials like wheat straw into biogas, a renewable energy source, while simultaneously creating digestate, a valuable by-product that may be utilised in farming. The several factors like the Carbon to Nitrogen ratio, particle size, moisture content was considered.

3.2.1.2 Converting wheat straw into biochar by pyrolysis

Pyrolysis is an appealing alternative in the realm of renewable energy technologies due to its carbon-negative nature. Through the heating of biomass in the absence of oxygen, feedstocks are broken down into charcoal, bio-oil, and biogas (Kung et al., 2015). Wheat straw is efficiently converted by the pyrolysis process into biochar, a useful and sustainable product that may enhance resource management, soil health, and carbon sequestration. This technique makes it possible to use agricultural wastes in a profitable and sustainable way.

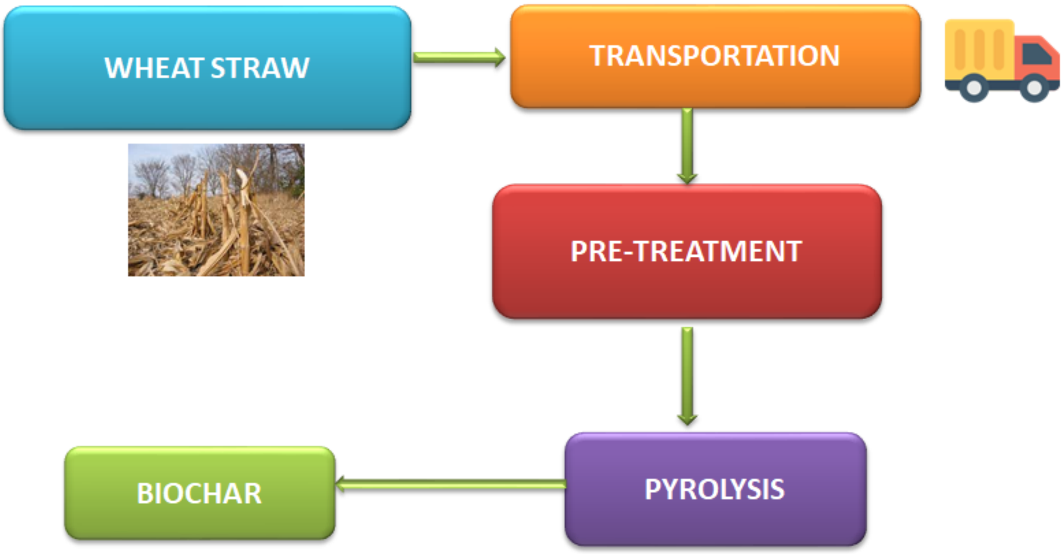

Figure 3.2 Flowchart of converting wheat straw into biochar by pyrolysis

A thorough flowchart demonstrating the pyrolysis process of turning wheat straw into biochar is shown in **Figure 3.2**. This diagram illustrates the successive phases in the pyrolysis process and provides a thorough explanation of how wheat straw is converted into biochar.

(1) Feedstock preparation: The process of preparing wheat straw for pyrolysis include gathering it and reducing its size into smaller bits, shredding, or drying it to make it more suitable for the pyrolysis reactor.

(2) Collection: To prepare them for additional processing, wheat straw is gathered from the fields or storage areas.

(3) Transport: Crop leftovers are sent to the pyrolysis plant that makes biochar.

(4) **Pre-treatment**: To increase their appropriateness for the formation of biochar, wheat straw may occasionally go through pre-treatment. Size reduction or drying are examples of pre-treatment.

(5) **Pyrolysis**: Crop wastes go through a high-temperature, oxygen-free process called pyrolysis. This releases gases and bio-oil and turns the organic material into biochar.

(6) **Production of biochar**: Biochar is a stable form of carbon that is abundant in pore spaces and is a solid by-product of pyrolysis. As such, it is a useful soil amendment.

(7) **Application of biochar**: The generated biochar may be applied as a soil supplement.

Properly produced and applied biochar has the potential to contribute to sustainable agriculture, carbon sequestration, and waste management, making pyrolysis a good method for biochar production from wheat straw.

3.2.1.3 Converting wheat straw into compost by composting

Composting involves regulated decomposition, the inherent breakdown of organic residues. This process converts raw organic waste materials into biologically stable, humic substances, serving as highly effective soil amendments (Cooperband, 2002). Composting is a natural and ecologically beneficial way to turn wheat straw into compost.

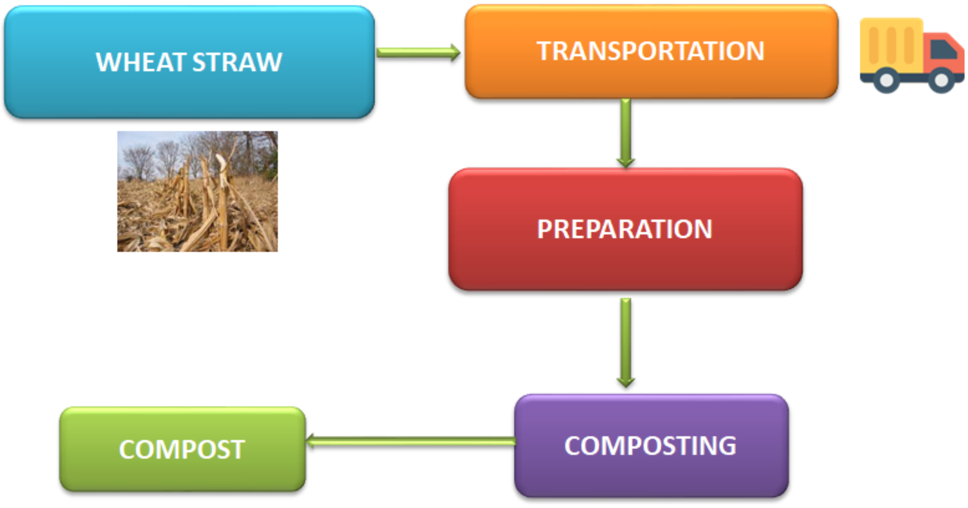

Figure 3.3 Flowchart of converting wheat straw into compost by composting

A detailed flow chart that describes the process of composting wheat straw is shown in **Figure 3.3**. The steps that are sequentially engaged in composting wheat straw are clearly illustrated in this illustration, which offers a comprehensive summary of the conversion process those results in compost.

(1) **Feedstock preparation**: Composting begins with the collection and preparation of wheat straw. For the straw to break down more easily, this can include slicing or shredding it into tiny pieces.

(2) **Collection:** To prepare them for additional processing, crop wastes are gathered from the fields or storage areas.

(3) **Transportation:** The composting plant receives the crop leftovers.

(4) **Preparation:** To improve the composting process and decrease their size, agricultural leftovers may be chopped or shredded at this stage.

(5) **Composting:** Green trash, food scraps, or manure are combined with the prepared agricultural residues and then composted. Microorganisms decompose the organic waste and produce heat as they break it down throughout the composting process.

(6) **Maturation:** The compost is allowed to cure or mature following the first stage of composting. This enables it to grow and stabilise into a stable, nutrient-rich soil amendment that may be used.

(7) **Compost utilization**: The fully grown compost may be added to the soil.

(8) **Soil health**: By raising the amount of organic matter in the soil, improving its structure, and encouraging beneficial microbial activity, compost helps the health of the soil.

Composting crop leftovers promotes soil health, gardening, and agricultural practises, which in turn leads to higher production and more sustainable land management practises.

3.2.1.4 Converting wheat straw into syngas by gasification

Gasification is the process of converting a solid or liquid feedstock into a usable and handy gaseous fuel or chemical feedstock that may be used to produce compounds with added value or burned to release energy. Pressure changes, a range of chemical reactions, heat and mass transfer mechanisms, and other intricate procedures are all part of the biomass gasification process (Baruah and Baruah, 2014). Wheat straw is converted into a gaseous mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and other gases by the thermochemical process of gasification, which produces syngas from wheat straw.

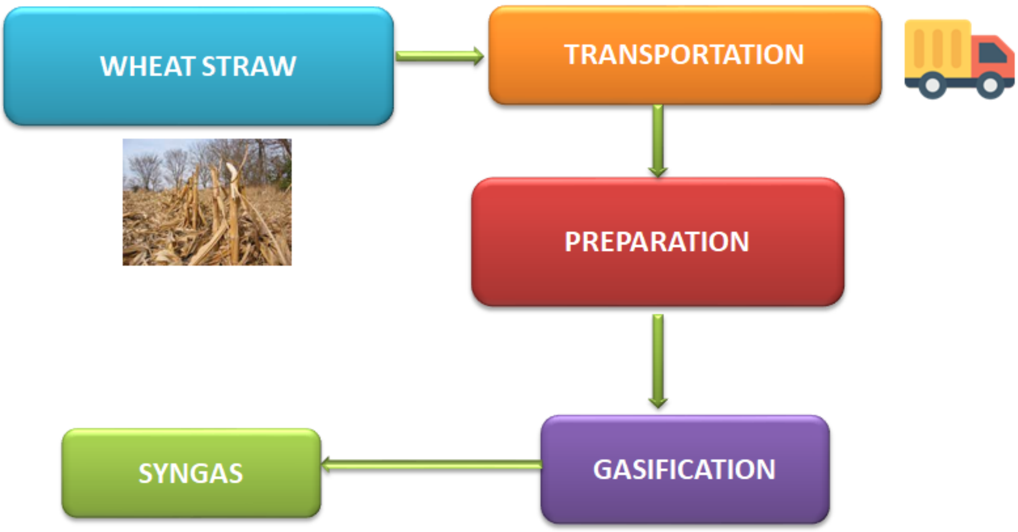

Figure 3.4 Flowchart of converting wheat straw into syngas by gasification

In **Figure 3.4,** a detailed flowchart illustrates the process of converting wheat straw into syngas through gasification. This visual representation delineates the sequential steps involved in the gasification process, providing a comprehensive overview of how wheat straw undergoes transformation into syngas.

(1) Feedstock preparation: The initial step in gasification is gathering and preparing wheat straw, an agricultural by-product. For best results during the gasification process, preparation usually includes drying the straw and breaking it into tiny pieces.

(2) Transport: After the wheat straw is ready, it is transported from the harvest region to the gasification facility.

(3) Gasification facility: The gasification plant, which has the infrastructure needed for the gasification process as well as gasification reactors, is the hub of the network. The conversion of wheat straw into syngas takes place in the gasification reactors, which is where the magic happens.

(4) **Cleaning and conditioning of gas:** The syngas produced during the gasification process might include tars, particles, and other pollutants. To guarantee that the syngas is of the highest quality, these pollutants are removed using gas clean-up equipment. Furthermore, syngas conditioning may be required to modify its characteristics and composition to satisfy needs for different applications.

(5) **Distribution or use of syngas:** After conditioning, the syngas is put to its intended use. Syngas is used for many different things, including as heating industrial buildings, producing chemicals, and generating energy.

From collecting of wheat straw to the use of syngas, which includes transportation, gasification, and environmental compliance, this offers a condensed summary of the critical processes in the supply chain network.

3.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is an analytical tool and systematic process that is outlined in the ISO 14040-14049 standards. All the fundamental terms, guiding ideas, methodological elements, and real-world LCA applications are covered by these standards. The goal of life cycle assessment (LCA) is to evaluate the environmental impact and energy efficiency of a system, process, or product from the point of production to the point of disposal (Prasad et al., 2021).

According to (Menoufi, 2011), Life Cycle Assessment (LCA) is a technique used to forecast and examine the influence of a sustainable environment concerning the life cycle of a product and a process. LCA can be described as an impartial procedure for appraising the environmental loads linked to a product, process, or operation by identifying and quantifying the consumption and release of energy and materials into the environment. It also aims to assess and apply strategies for making environmental enhancements.

According to Society of Environmental Toxicology and Chemistry (SETOC), the term Life-cycle assessment (LCA) is defined as “an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvements” (SETAC, 1993). Life-cycle assessment (LCA) is one of the various methodologies available for evaluating environmental effects. It aids in broadening the viewpoint outside the waste management system (Ekvall et al., 2007).

By replacing processes or sub-processes that have a more noticeable negative impact on the environment with alternative processes or sub-processes, the LCA study's primary goal is to reduce the environmental burden. The goal of this swap is to increase the product's overall environmental friendliness (Hiloidhari et al., 2017).

There are four major stages in the LCA study's organised methodology. The objectives, limits, and functional unit of the research are first carefully defined during the goal and scope definition phase. The second stage, known as the Life Cycle inventory (LCI), comprises a thorough examination of all inputs and outputs to develop a full model of the product's lifespan. In the third step, referred to as the Life Cycle Impact Assessment (LCIA), every input and output connected to the product are evaluated for their environmental impact. The study's results are painstakingly evaluated and summarised in the final phase, Interpretation, which results in suggestions for potential actions to lessen the product's environmental effect (Rathore et al., 2013).

3.3.1 Framework of LCA

The Life Cycle Assessment (LCA) framework is organised in line with the ISO 14040 model, which offers a globally accepted and standardised structure for carrying out LCA. ISO stands for International Organization for Standardization.

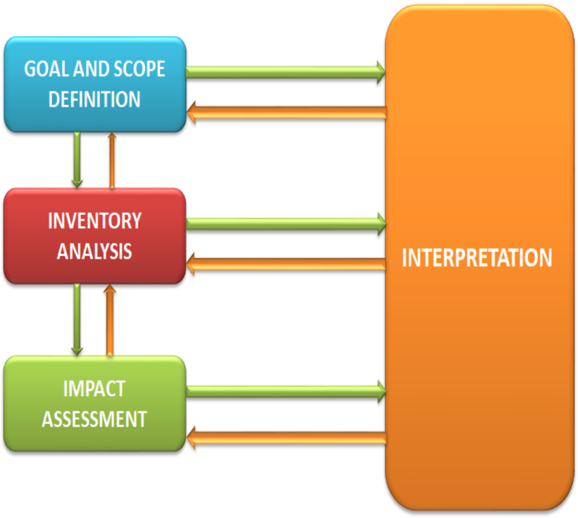

Figure 3.5 ISO 14040 Framework model

The ISO 14040 Framework model is shown in **Figure 3.5**. The ISO 14040 standard provides a systematic method to life cycle assessment (LCA), which is outlined in this visual illustration.

(1) Goal and scope definition

The goals and parameters of the evaluation are set at this first stage. This entails defining the system, process, or product as well as its functional unit and the environmental impact categories that need to be assessed.

(2) Inventory analysis

At every stage of the life cycle of a product or process, data is gathered and arranged to provide a thorough inventory of all inputs, including energy and raw materials, and outputs, including waste and emissions. Quantifying the inputs and outputs from the environment requires completing this phase.

(3) Impact assessment

In this stage, the gathered inventory data is examined to determine any possible effects on the environment. To comprehend the whole environmental footprint, a few effect categories are considered, including greenhouse gas emissions.

(4) Interpretation

The final phase involves the interpretation of the results. This includes assessing the significance of the environmental impacts, identifying opportunities for improvement, and making informed decisions based on the LCA findings.

3.3.2 The system boundary of Life Cycle Assessment framework over a product's life cycle

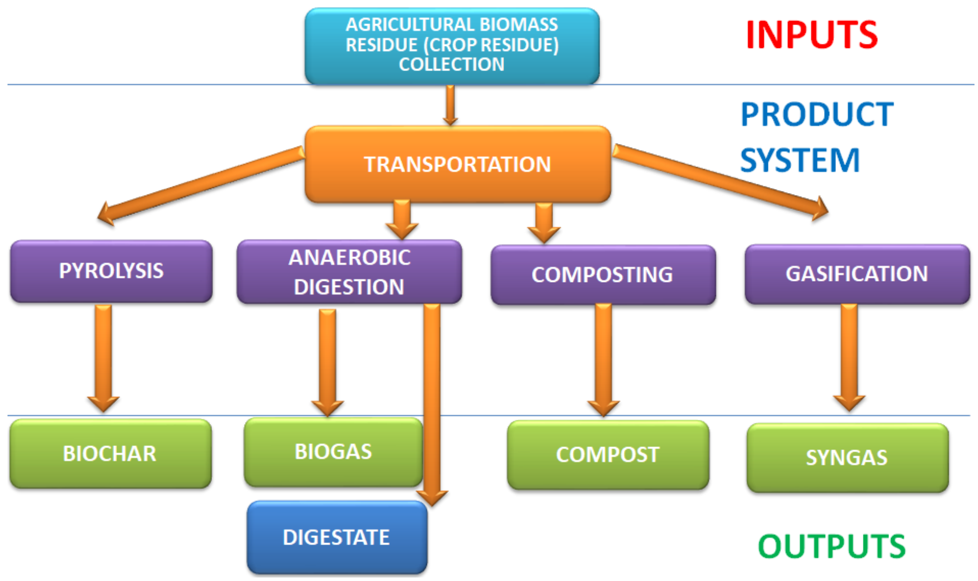

Figure 3.6 System boundary of LCA by ISO 14040 framework model

This **Figure 3.6** illustrates the system boundary for the wheat straw conversion to useful possible outputs. There are three main phases in the system boundary classification. They are:

(1) **Inputs:** The material, energy, and resources that are utilised or consumed during a certain phase of a product's life cycle are referred to as inputs.

Interpretation for the study: According to the study, it includes the wheat straw that is needed to convert into useful product through various processes.

(2) **Product system:** The product system delineates the parameters and extent of the Life Cycle Assessment (LCA) and indicates the steps that will be part of the evaluation. It facilitates the definition of the system being studied, making a thorough assessment of the effects on the environment possible.

Interpretation for the study: According to the study, it includes the transportation phase of transferring wheat straw into the facilities which includes anaerobic digestion, pyrolysis, composting, and gasification. It also includes the pre-treatment and the four techniques that are converted into useful products.

(3) **Outputs:** Actions and choices aiming at lowering environmental effects and enhancing product sustainability are guided by suggestions and decision-support data based on the LCA results.

Interpretation for the study: According to the study, it includes the final output from those processes which results in the production of biogas, biochar, compost, and syngas.

3.3.3 SimaPro software

To assist assure consistency and dependability in evaluating the environmental performance of goods, processes, or systems, the ISO 14040 model offers an organised and methodical way to conducting life cycle assessments (LCAs). In this study, the analysis is carried out using SimaPro 9 software.

SimaPro software, in particular version 9, created by PRé Consultants, was used to conduct the analysis in this study. The software's geographical provenance is highlighted by

PRé Consultants, a sustainability consulting organization with its headquarters in the Netherlands. SimaPro is well-known and often utilised life cycle assessment (LCA) software. Throughout their whole life cycle, from raw material extraction to manufacture, usage, and disposal, goods, processes, or systems are evaluated for their environmental effect using the life cycle assessment (LCA) technique. SimaPro was created to make the LCA process easier and more efficient.

3.4 Inventory analyses consideration and calculation

There are a few key factors to keep in mind while converting wheat straw into biochar, biogas, compost, and syngas through experimentation. These factors consider a number of experiment-related factors, such as practical viability, safety, and environmental effect. These inputs for the analysis were imported to the SimaPro software to provide the clear analysis report. This is an extensive list of things that are considered and assumed for this work.

(1) The transportation distance in which the feedstock is transported from harvest area to the process facility is considered as 100 km. The transportation distance between the facility and the harvest location is shown graphically in **Figure 3.7.**

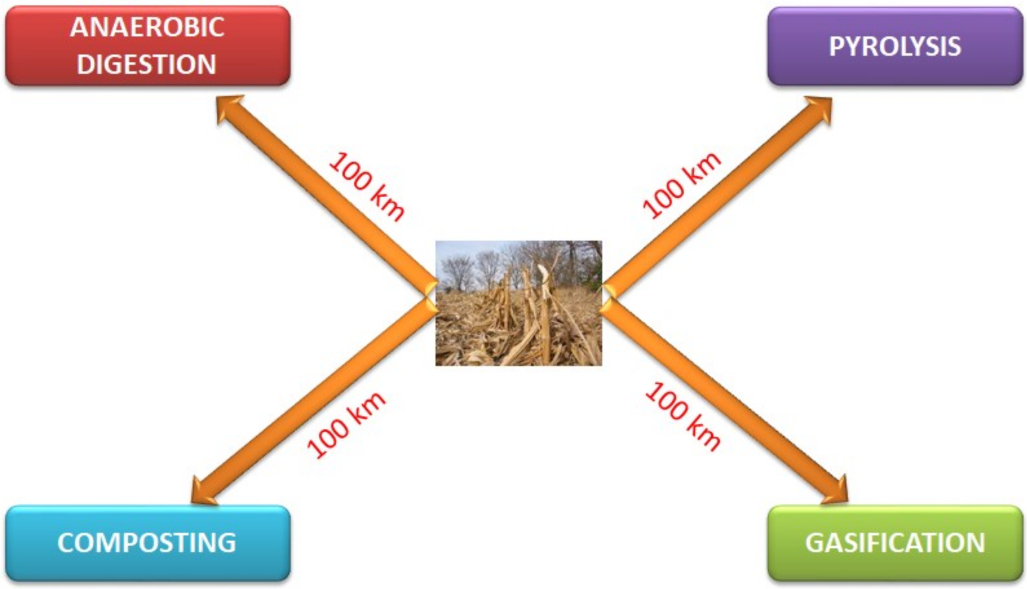

Figure 3.7 The transportation distance from the harvest area to the facility

(2) The quantity of wheat straw (input) to produce biochar, biogas, compost, and syngas is assumed as 1000 kg.

(3) The truck used to collect the 1000 kg of wheat straw is Straight truck.

(4) To ensure effective conversion, the wheat straw was carefully chosen to be free of impurities and dried appropriately. **Table 3.3** lists common variables and the corresponding presumptions for different disposal methods.

Table 3.3 Common factors and associated assumptions for several disposal techniques

Technique	Wheat straw (raw material) (kg)	Transportation (km)	Power (kWh)	Fuel burnt (MJ)
Anaerobic digestion	1000	100	83	35
Pyrolysis	1000	100	31	30
Composting	1000	100	17.7	35
Gasification	1000	100	83	40

(5) According to research on the anaerobic digestion of wheat straw by (Alsamaq et al., 2015), several inputs were taken into consideration for our work. Electricity is estimated from the job to be 83 kWh at low voltage. It is estimated that 35 MJ of fuel were burnt in the agricultural equipment. The necessary heat is calculated to be 394 MJ.

(6) Several assumptions were considered for the study on the pyrolysis conversion of wheat straw to biochar (Veracoechea, 2023). Several inputs for analysis are obtained from this study. 31 kWh power consumption is assumed. 30 MJ of fuel is thought to have been consumed in the farm equipment. The necessary heat is assumed as 425 MJ.

(7) Several inputs were taken into consideration for our work based on the findings of a study conducted on the composting of wheat straw (Pergola et al., 2020). This takes into account the 17.7 kWh of electricity and the 35 MJ of fuel that is presumably burned in the farm equipment.

(8) According to (Nguyen et al., 2013), several assumptions and data are taken into consideration for gasification which includes, electricity for the operation as 83 kWh. The heat required is assumed as 650 MJ. The diesel burned in the agricultural machinery is assumed as 40 MJ.

These are the primary sources that were considered throughout the analysis.

Chapter 4 Results and Discussion

4.1 Efficient disposal technique assessment

To evaluate and select the most effective waste disposal method among anaerobic digestion, gasification, composting, and pyrolysis, a thorough analysis was conducted using SimaPro 9 software. This assessment encompassed the application of three distinct methodologies namely, Intergovernmental Panel on Climate Change (IPCC) Global Warming Potential (GWP) 100a, Greenhouse Gas Protocol, and Impact 2002+. The primary objective of this analysis was to identify the most appropriate technique for managing agricultural biomass residue.

An in-depth analysis of the sustainability factors and environmental effects related to each waste disposal strategy was made possible by this thorough study. In order to give a comprehensive view of the best ecologically friendly and effective strategy for managing agricultural biomass residue, the study used a variety of assessment approaches.

In this study, three different methods were used to determine the best disposal technique method that has least environment impact and better sustainability. They are:

1. Intergovernmental Panel on Climate Change (IPCC) 2013 Global warming potential 100a
2. Greenhouse gas protocol
3. Impact 2002+

4.1.1 IPCC 2013 Global Warming Potential 100a

"IPCC GWP 100a" refers to the Global Warming Potential (GWP) values calculated over a 100-year time period, as defined by the Intergovernmental Panel on Climate Change (IPCC). GWP is a way of measuring how much heat-trapping capability a greenhouse gas has over a specified time frame compared to carbon dioxide (CO_2), which is given a GWP value of 1. It is a tool used to evaluate the impact of various greenhouse gases on global warming.

To conduct a life cycle assessment that encompasses the computation of greenhouse gas emissions by utilizing the IPCC GWP values for a 100-year time span. This process entails evaluating the influence of various greenhouse gases released throughout the life cycle of a product and converting them into CO_2-equivalents using their GWP 100a values as stipulated by the IPCC. This analysis aids in comprehending the climate impact of the emissions linked to a product or process.

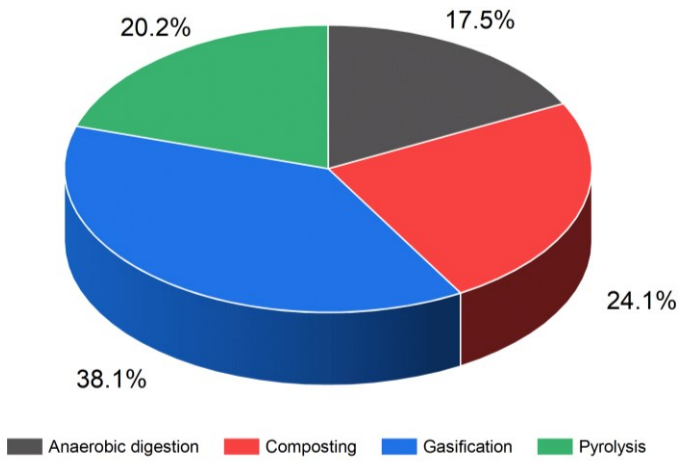

Figure 4.1 Global Warming Potential percentage using the IPCC GWP 100a method

The findings of the IPCC 2013 Global Warming Potential 100a approach are shown in **Figure 4.1**. From the results in IPCC GWP 100a, anaerobic digestion which results in production of biogas is said to be the most significant technique to dispose the wheat straw which causes only 17.5% of the global warming potential which is followed by pyrolysis with 20.2%.

4.1.1.1 Ranking of four methods with respect to IPCC GWP 100a

The numbers below represent the ranking order of disposal techniques from least GWP to high GWP in the span of 100 years:

(1) Anaerobic digestion to produce biogas.

(2) Pyrolysis to produce biochar.

(3) Composting to produce compost.

(4) Gasification to produce syngas.

4.1.1.2 Significance of anaerobic digestion on GWP

Methane (CH_4) is a powerful greenhouse gas that anaerobic digestion can collect and use, which contributes to its lower Global Warming Potential (GWP) when compared to various other waste management and energy generation techniques. Because of the high methane content of the biogas generated, collecting it lowers the net greenhouse gas pollution. Utilising biogas as a sustainable energy source replaces fossil fuels, lowering the emissions brought on by burning coal, oil, or natural gas.

Anaerobic digestion reduces methane emissions compared to uncontrolled decomposition of organic waste. Uncontrolled decomposition in landfills or other environments can release methane directly into the atmosphere, contributing to global warming. Anaerobic digestion provides a controlled environment for organic material decomposition, minimizing these emissions.

Anaerobic digestion also produces digestate, a nutrient-rich by-product that can take the place of energy-intensive synthetic fertilisers and lower emissions related to fertiliser manufacture. The decreased GWP of anaerobic digestion is a result of several elements working together. However, variables like feedstock, system performance, and management techniques might affect the GWP. Anaerobic digestion may be made more environmentally sustainable by lowering its GWP by on-going advancements in system design, feedstock selection, and effective biogas and digestate management.

4.1.2 Greenhouse Gas Protocol

A well-known methodology for evaluating greenhouse gas emissions, the Greenhouse Gas Protocol (GHG) approach, was incorporated by SimaPro. This approach ensured consistent and precise emissions computations by adhering to GHG Protocol criteria. The evaluation of historical carbon footprints for products, processes, or organisations was made easier by SimaPro's GHG Protocol technique. This methodology facilitates the computation of emissions in compliance with extensively recognised norms, augmenting reliability, and comparability for interested parties. For companies looking to track and lower their historical carbon emissions and enhance environmental sustainability in the past, it was an essential tool.

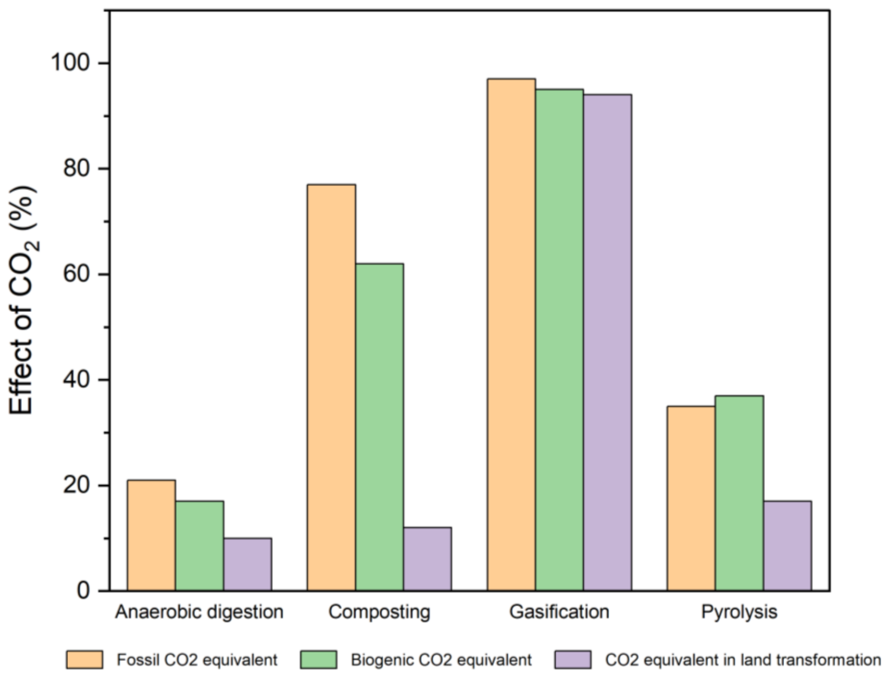

Figure 4.2 Percentage effect of CO_2 by Greenhouse Gas Protocol method

In **Figure 4.2**, the outcomes obtained through the Greenhouse Gas Protocol method are depicted. This visual representation offers insights into the environmental impact of the analyzed data, highlighting results based on the Greenhouse Gas Protocol methodology. This method describes three important factors namely fossil CO_2 equivalent, biogenic CO_2 equivalent and CO_2 equivalent in land transformation. The information from **Figure 4.2** indicates that anaerobic digestion has a lower percentage impact on CO_2 when compared to alternative techniques. Specifically, its effects are consistently under 25% in three essential factors: fossil CO_2 equivalent, biogenic CO_2 equivalent, and CO_2 equivalent in land transformation. The next best technique is pyrolysis where all the effects of CO_2 are less than 40%.

The term "Fossil CO_2 equivalent" refers to a notion that has been modified or interpreted specifically for the SimaPro software programme. It might be used to describe the measurement of emissions from burning fossil fuels represented as CO_2-equivalents, taking into consideration the fluctuating global warming potential (GWP) values of various greenhouse gases over a certain period.

The phrase "biogenic CO_2 equivalent" is used in carbon accounting, particularly in life cycle evaluations. In our situation, it stands for agricultural biomass residue, and it reflects carbon dioxide (CO_2) emissions from biological or renewable sources. Because of the natural carbon cycle, in which CO_2 absorbed by plants during growth balances CO_2 emitted during burning, biogenic emissions which contrast with CO_2 emissions from fossil fuel are sometimes seen as carbon neutral over a predetermined period. When evaluating the environmental effects of bio-based goods or renewable energy sources, accounting for biogenic CO_2 equivalent is essential. It takes sustainability, land-use changes, and time spans into account.

"CO_2 equivalent in land transformation" describes the emissions of carbon dioxide equivalent linked to modifications in land use or land cover. Deforestation, urbanisation, and the growth of agriculture are examples of land transformations that can release carbon held in soil and plants and increase greenhouse gas emissions. To take into consideration other greenhouse gases like nitrous oxide and methane, these emissions are given in CO_2 equivalent units. Understanding the environmental effects of land use changes, notably their involvement in global climate change and the loss of carbon, requires accurate evaluation of CO_2 equivalent in land transformation.

4.1.2.1 Ranking of four methods with respect to Greenhouse Gas Protocol

The ranking below represents the order of disposal techniques based on GHG approach:

(1) Anaerobic digestion to produce biogas.

(2) Pyrolysis to produce biochar.

(3) Composting to produce compost.

(4) Gasification to produce syngas.

4.1.2.2 Significance of anaerobic digestion on Greenhouse Gas Protocol

Anaerobic digestion is shown to be the most feasible and ecologically benign technique of disposing of garbage, with the least negative effects on the environment, after the analysis. Because it reduces harmful impacts on the environment, anaerobic digestion stands out as a very practical waste disposal technique. However, determining if it is the "best" option relies on a number of variables, such as the type of trash, the environment, and sustainability goals.

4.1.3 Impact 2002+

Impact 2002+ is an established life cycle impact assessment methodology integrated into SimaPro software for conducting comprehensive environmental assessments. It enables to evaluate the environmental impacts of products and processes across various categories like ionising radiation, ozone layer depletion, aquatic Eco toxicity, land occupation, global warming, and non-renewable energy. Impact 2002+ builds upon its predecessor, Impact 2002, and is widely recognized for its thoroughness in assessing environmental consequences throughout a product or process's life cycle. The technique estimates the possible environmental effects of a product or process over the course of its life cycle by taking into consideration many impact categories as well as different emissions and resource consumption metrics.

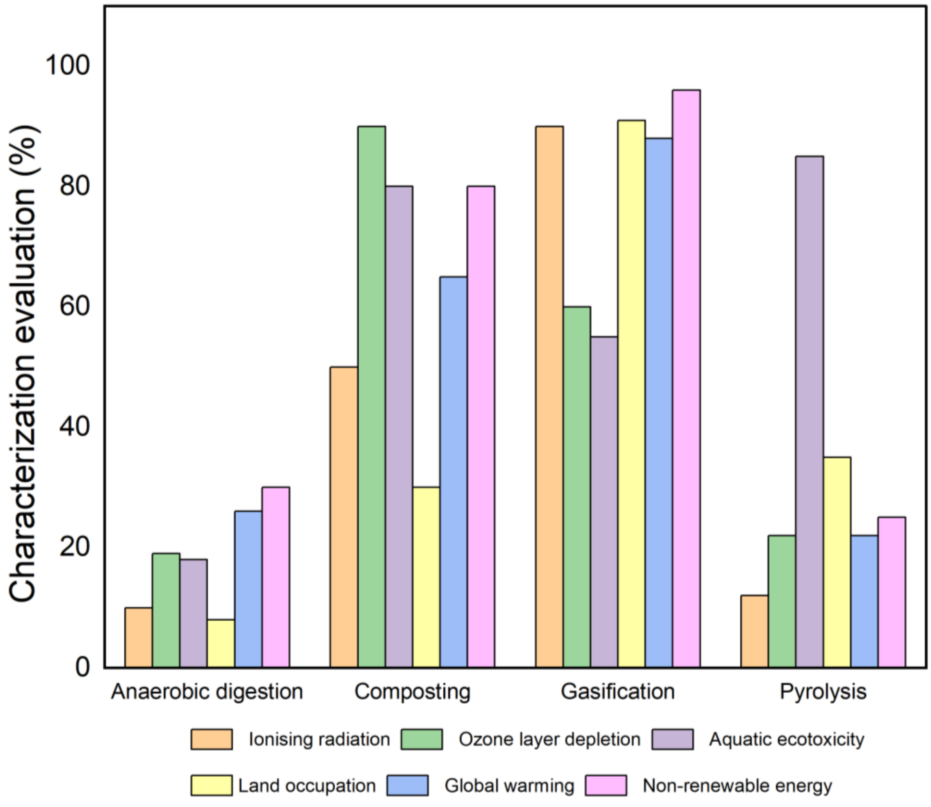

Figure 4.3 Percentage impacts of six factors using the Impact 2002+ method

In **Figure 4.3**, the outcomes obtained from the IMPACT 2002+ method are illustrated. This visual representation provides insights into the environmental impact of the analyzed data, emphasizing the results derived from the IMPACT 2002+ methodology. In this analysis, several factors like ionising radiation, ozone layer depletion, aquatic ecotoxicity, land occupation, global warming, and non-renewable energy are studied. The analysis on the **Figure 4.3** shows that anaerobic digestion performs better than the other three methods in every effect category. Anaerobic digestion is the best method since its characterisation evaluations for all variables are less than 30%. Pyrolysis follows closely, showing comparable effects for most parameters, apart from aquatic ecotoxicity, where it approaches 80%.

4.1.3.1 Ranking of four methods based on Impact 2002+ method

The ranking below represents the order of disposal techniques based on Impact 2002+ method:

(1) Anaerobic digestion to produce biogas.

(2) Pyrolysis to produce biochar.

(3) Composting to produce compost.

(4) Gasification to produce syngas.

4.1.3.2 Significance of anaerobic digestion on Impact 2002+

Among all the factors, anaerobic digestion to produce biogas and pyrolysis process on producing Biochar were said to be the best as they cause less environmental impact than the rest.

Specifically, anaerobic digestion is indirectly connected to a decrease in ozone layer depletion. It may be possible to lessen the need for fossil fuels and synthetic fertilisers by turning agricultural biomass leftovers into biogas and organic fertilisers (digestate). Reduced use of synthetic fertilisers results in lower emissions of nitrous oxide (N_2O), a major contributor to the depletion of the ozone layer. Additionally, using biogas as a sustainable energy source can lessen the amount of fossil fuels used, which may produce chemicals that deplete the ozone layer.

4.1.4 Summary

The results of the several SimaPro techniques make it clear that anaerobic digestion has the most positive environmental impact. The technique that has the fewest detrimental effects on the environment is anaerobic digestion.

4.2 Social aspect analyses for the four agricultural biomass waste disposals scenarios

The disposal of wheat straw is a complex challenge in the context of sustainable farming practises, requiring thorough assessment of its effects on the environment and society. Wheat straw is a by-product of one of the world's staple crops and has traditionally been managed using conventional methods. However, as sustainable waste management has gained more attention, cutting-edge technologies like anaerobic digestion, gasification, composting, and pyrolysis have emerged as viable solutions. The social aspects of using pyrolysis, gasification, anaerobic digestion, and composting to dispose of wheat straw are examined in this paper.

4.2.1 Characterization of damage statement

SimaPro's EPS 2015dx technique is utilised for the analysis. Environmental Priority Strategies is a stand-alone acronym. The impact assessment approach known as EPS 2015dx is focused on damage. The Environmental Priority Strategies (EPS) in Product Design system includes it as a component.

The UN Department of Economic and Social Affairs presented a variety of perspectives that should be included in the social analysis, including changing social attitudes and human health. The dx version does not include climatic consequences from secondary particles (Racz et al. 2018). The EPS 2015dx method is designed to evaluate the prevalence and impacts of diseases, notably cancer, asthma, and diarrhoea, and it exclusively compares the consumption of abiotic resources across different scenarios related to wheat straw disposal.

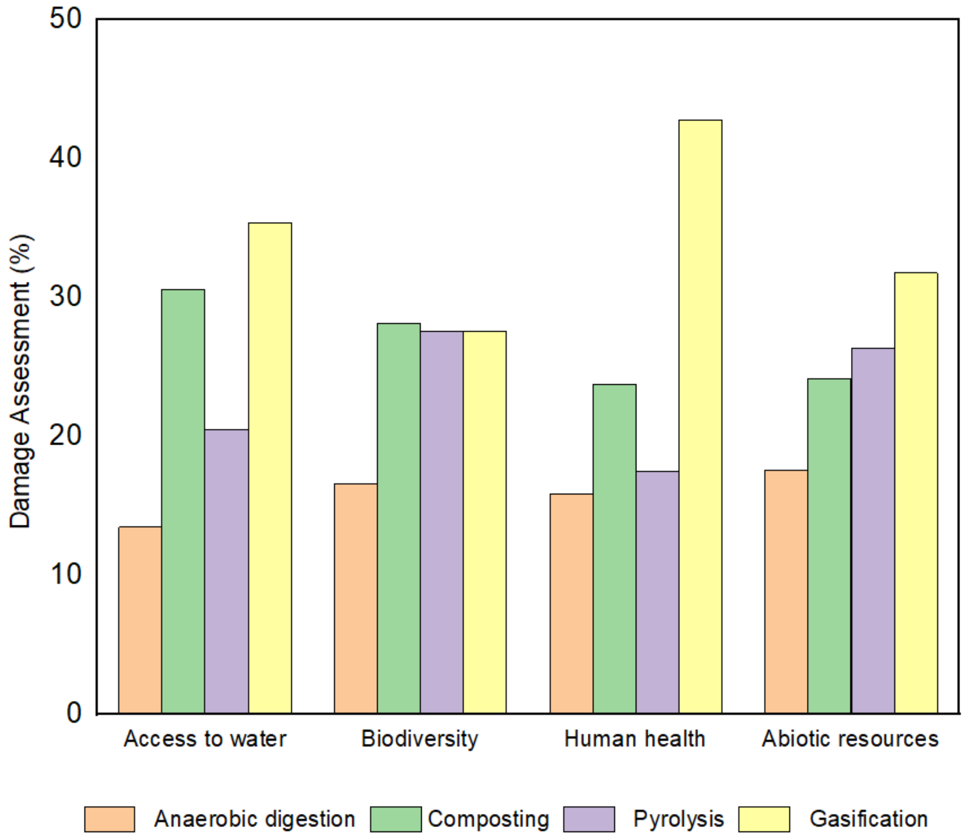

Figure 4.4 Assessment of Damage Characterization using the EPS 2015dx method

In **Figure 4.4**, the characterization of damage assessment is presented, encompassing key factors such as access to water, biodiversity, human health, and abiotic resources. This visual representation provides an overview of the assessed damages across these critical dimensions, offering insights into the broader environmental implications associated with the analyzed data. The effects of anaerobic digestion with these variables are less than 20% and it is the best option when compared to the rest.

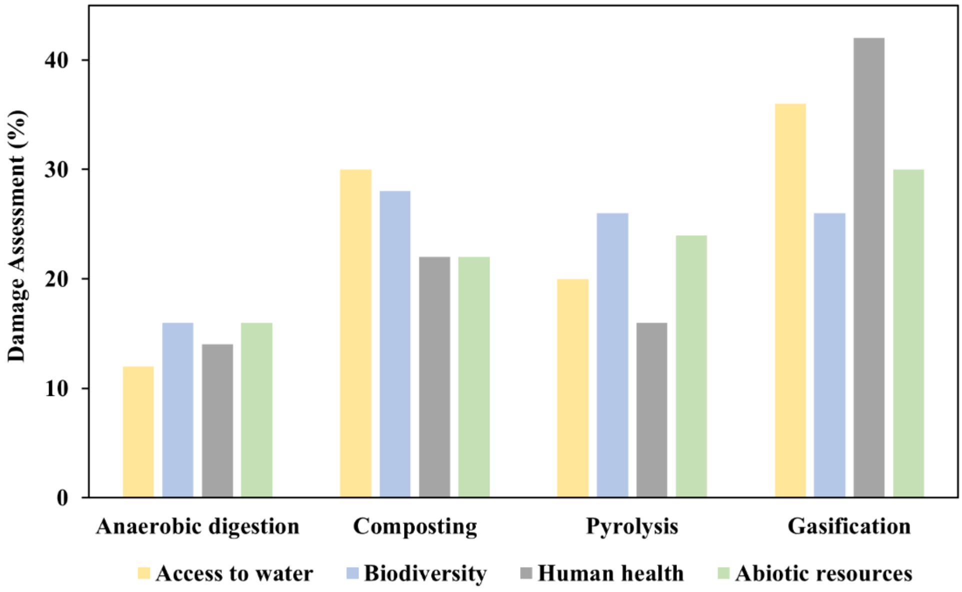

Figure 4.5 Percentage of Damage assessment for the four techniques using EPS 2015dx method

Figure 4.5 presents the characterization of damage assessment, encompassing key factors such as access to water, biodiversity, human health, and abiotic resources. This visual representation provides an overview of the assessed damages across these critical dimensions and offers insights into the broader environmental implications associated with the data.

4.2.2 Interpretation

Four primary metrics are selected for interpretation in the analysis. They are abiotic resources, human health, biodiversity, and water availability. The findings of the damage assessment using the EPS 2015dx approach show that:

Table 4.1 Percentage of damage assessment by EPS 2015dx method

Technique	Access to water	Biodiversity	Human health	Abiotic resources
Anaerobic digestion	13.5	16.6	15.9	17.6
Pyrolysis	20.5	27.6	17.5	26.4
Composting	30.6	28.2	23.8	24.2
Gasification	35.4	27.6	42.8	31.8

The four methods and the appropriate percentages for damage assessment are shown in **Table 4.1**. These are the weightage of the four different metrics with respect to various techniques. When compared to the other four scenarios, the anaerobic digestion scenario had the least amount of environmental harm across all impact regions. When compared to all other scenarios, the gasification scenario of turning wheat straw into syngas has the greatest impact on environmental degradation, except for biodiversity. In the next phase of the analysis, the emphasis will be on determining the most effective supply chain network for the process, clearly resulting in a reduction in emissions. The analysis will specifically target the identification of a supply chain configuration that contributes to a noticeable decrease in emissions. This strategic approach aims to optimize the process and align it with environmentally friendly practices.

4.3 Supply chain network

An extensive Life Cycle Assessment (LCA) of wheat straw produced data that categorically supported the use of anaerobic digestion as a more sustainable and ecologically friendly option. When compared to alternative utilisation techniques, anaerobic digestion has demonstrated a considerably lower environmental effect, proving its relative advantage. This intriguing discovery has led to the supply chain model actively investigating the possibility of integrating anaerobic digestion. The social aspect research confirms that anaerobic digestion has the least negative effect on the environment.

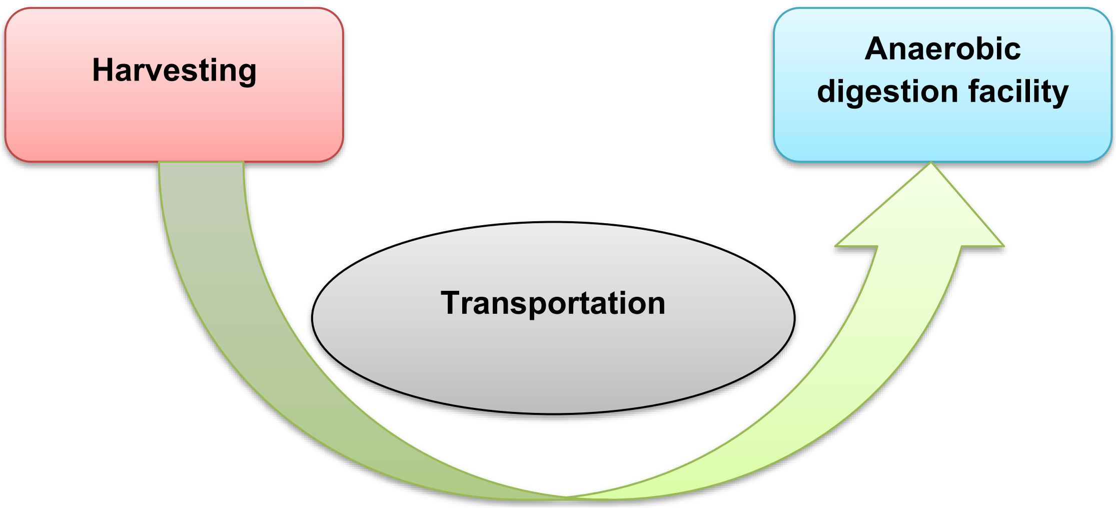

Figure 4.6 Supply chain network from collection to delivery at anaerobic digestion facility

In **Figure 4.6**, the supply chain network for the anaerobic digestion process is depicted and thoroughly examined considering these findings. This visual representation encompasses the entire process, starting from the initial harvesting step through to the anaerobic digestion facility.

The harvesting part in the **Figure 4.6** includes both the collection and loading.

Collection: Agricultural biomass residue (Wheat straw) is typically collected from fields after crop harvesting. This can involve the use of specialized equipment like balers or loaders to create compact and manageable bales or stacks.

Loading: The collected wheat straw is loaded onto the straight truck.

Transport: The straight truck transports the biomass residue to anaerobic digestion plant.

Unloading: At the destination, the biomass residue is unloaded from the truck.

4.3.1 Transportation cost involved from harvesting to anaerobic digestion

In this analysis, several assumptions were considered.

- ❖ The transportation distance is assumed as 100 km.
- ❖ The truck used to collect the 1000 kg of wheat straw is Straight truck. Agricultural biomass residue can be transferred by straight truck operations. Utilising straight trucks, agricultural biomass residue may be gathered, moved, and stored in many forms. These trucks are ideal for moving agricultural biomass inside and between farms, processing plants, and other sites since they are well-suited for local and regional transportation demands.
- ❖ Usually, wheat straw is accessible following the harvest of wheat harvests. In Canada, the spring and summer months are the main times for producing wheat, with harvest taking place in late summer or early fall. The harvest may occur precisely in June, July, August, and September. As a result, the study takes place over the course of four months, or 120 days.
- ❖ The analysis is taken for 5 days among the 120 days' time frame.

- Average waiting time for loading and unloading of the wheat straw on the truck would be 1.5 hours in total.

4.3.2 Estimation of transportation costs from harvesting to the facility

(1) Average trip travel distance kilo meter (km)

From the assumption, the average trip distance is 100 km.

(2) Average travel speed in kilo meter per hour (kmph)

Barton et al., (2006) has used the average travel speed as 56 kmph.

(3) Average waiting time for loading / unloading per trip hour (hr)

From the assumption, the average waiting time is 1.5 hours.

(4) Total waiting time for loading / unloading for 5 days (hr)

$$\textbf{Total waiting time for loading/ unloading} = \textbf{Average waiting time} \times \textbf{Number of days} \quad \textbf{(4.1)}$$

Total waiting time for loading / unloading = 1.5 × 5

Total waiting time for loading / unloading = 7.5 hr.

(5) Total distance travelled (km)

$$\textbf{Total distance travelled} = \textbf{Average trip travel distance} \times \textbf{Number of trips per day} \times \textbf{Number of days worked} \quad \textbf{(4.2)}$$

Total distance travelled= 100 × 1 × 5

Total distance travelled= 500 km.

(6) Average driving time (hr)

$$\textbf{Average driving time per day} = \frac{\textbf{Average distance}}{\textbf{Average travel speed}} \quad \textbf{(4.3)}$$

$$\text{Average driving time per day} = \frac{100}{56}$$

Average driving time per day = 1.78 hours

$$\textbf{Average driving time} = \textbf{Average driving time per day} \times \textbf{Number of days worked} \quad \textbf{(4.4)}$$

Average driving time = 1.78 × 5

Average driving time = 8.9 hours

(7) Per vehicle fuel consumption rate (litres / 100 km)

Barton et al., (2006) has considered per vehicle fuel consumption rate as 37 litres/100 km.

(8) Vehicle operational costs ($)

(a) Number of drivers per trip is 1.

(b) Total driver cost

Barton et al., (2006) has considered the driver base pay as $19.25/ hr.

$$\textbf{Total driver cost} = \textbf{Driver base pay} \times \textbf{Total hours} \quad \textbf{(4.5)}$$

Total driver cost = $19.25 × (7.5 + 8.9 hours)

Total driver cost = $315.7.

(c) Total fuel consumption costs

Total distance = 500 kms

Current fuel cost is assumed as $1.50/L.

Rated fuel efficiency = 37L/100 km.

Total fuel consumption costs are $227.5.

(d) Miscellaneous costs

Other miscellaneous costs are assumed as $200.

(e) Total vehicle operational costs

$$\textbf{Total vehicle operational costs} = \textbf{Fuel cost} + \textbf{Driver cost} + \textbf{Miscellaneous costs} \quad \textbf{(4.6)}$$

Total vehicle operational costs = \$315.7 + \$227.5 + \$200

Total vehicle operational costs = \$743.

This value serves as an indicator of the overall operational expenses incurred when transporting wheat straw from the harvest location to the Anaerobic digestion facility. It represents the comprehensive costs associated with the entire process of collecting, loading, and transporting the wheat straw.

These expenses encompass various components, including fuel costs, driver costs, and any other costs involved in the transportation operation. Essentially, it encapsulates the full financial picture of transferring wheat straw to the anaerobic digestion site, providing a clear understanding of the investment required for this crucial phase of the supply chain.

4.4 Greenhouse gas emission reduction strategies by optimization of supply chain network

The optimisation of supply chain networks has become a critical strategy in the quickly changing world of modern business, with far-reaching effects that go beyond conventional measures of efficacy and cost. One important consideration in supply chain optimisation is environmental sustainability. Here are the few main areas where environmental sustainability can be increased.

4.4.1 Optimized transportation by implementing green logistics

"Greenness" has evolved to be used as a code term for a variety of environmental issues and is often seen favourably, according to (Rodrigue et al., 2017). It is used to imply environmental compatibility, which is why it is advantageous, much like "logistics." The combination of the two terms denotes an efficient and ecologically friendly system of transportation and distribution. Many people find the word appealing and highly attractive.

Incorporating ecologically friendly practises into transportation and logistics operations is known as green logistics, often referred to as sustainable or eco-friendly logistics.

Reducing the environmental effect of supply chain-related transportation operations is the main objective of green logistics. Reducing energy use, carbon emissions, and the ecological footprint overall are all part of this. The usage of automobiles with reduced emissions or vehicles that run on alternative fuels, such hybrid or electric cars will be helpful. By using these alternatives, greenhouse gas emissions and reliance on fossil fuels are reduced.

4.4.1.1 Electric trucks in supply chain optimization: A paradigm shift in design

In the subsequent phase of the analysis, the focus shifts to a comparison between a conventional fuel-powered straight truck and an electric truck for supply chain purposes. This comparison aims to assess their respective performance and suitability within the broader context of logistics and distribution.

The Renault D.Z.E electric truck is the one used in the investigation (Liimatainen et al., 2019). The truck can carry a maximum of 16,000 kg of weight.

From the specifications in (Renault trucks 2018), several assumptions are made. They are:

(1) Battery capacity is considered as 300 kilo watt hour (kWh).

(2) Range is considered as 300 km.

(3) Energy consumption

$$\textbf{Energy consumption} = \frac{\textbf{Battery capacity}}{\textbf{Range}} \qquad \textbf{(4.7)}$$

$$\text{Energy consumption} = \frac{300}{300}$$

= 1 kWh/km.

(4) Total distance is 500 km.

(5) Electricity rate: Electricity rate according to (energyhub.org, 2024) is noted as \$0.192 / kWh.

(6) Total electric truck consumption costs

$$\textbf{Total electric truck consumption costs} = \textbf{Energy consumption} \times \textbf{Total distance} \times \textbf{Electricity rate} \qquad \textbf{(4.8)}$$

$$= 1 \times 500 \times 0.192$$

$$= \$96.$$

(7) From the previous results for fuel truck, the driver costs are taken as \$315.7.

(8) Miscellaneous costs = other miscellaneous costs are assumed as \$200.

(9) Total operating costs

$$\textbf{Total operating costs} = \textbf{Total electric truck consumption costs} + \textbf{driver cost} + \textbf{miscellaneous costs} \qquad \textbf{(4.9)}$$

$$= \$96 + \$315.7 + \$200$$

$$= \$611.$$

From both the analysis, it is evident that total operating costs of electric truck are lesser than that of the commercial fuel truck. A comparison of the consumption rate and overall operating costs of an electric vehicle and a commercial gasoline truck is shown in **Figure 4.7**. In terms of consumption rates and overall running expenses, this visual depiction provides a thorough study of the performance indicators, enabling a thorough evaluation of the economic and efficient features related to the electric car and the commercial gasoline truck.

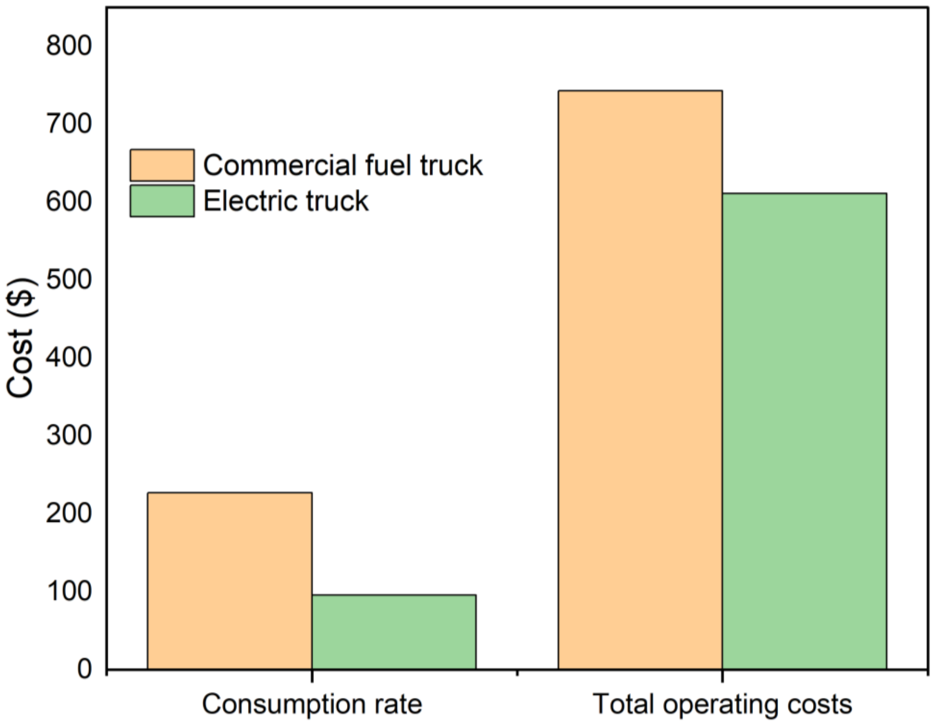

Figure 4.7 Comparison of consumption rate and total operating costs of electric vehicle and fuel truck

From the **Figure 4.7**, it is very clear that the consumption rate and total operating costs are lesser for electric vehicle than the commercial fuel truck. The consumption rate of the electric truck is $96 which is lesser than that of commercial truck with $227.5. Similarly, the total operating costs of electric truck is $611 which is lesser than that of commercial truck with $743.

4.4.2 Optimized transportation by reducing the transportation distance

In the intricate web of modern supply chain management, the reduction of transportation distance emerges as a cornerstone strategy for organizations seeking heightened efficiency and environmental sustainability. The ReCiPe approach stands out among the other LCA techniques since it is one of the most modern and sophisticated, offering the widest range of mid-point effect categories and a worldwide impact calculation mechanism (Goedkoop et al., 2013).

One of the most sophisticated LCA approaches, ReCiPe 2016 offers the widest range of mid-point impact categories. The proportion of kg CO_2 equivalent in relation to global warming is the primary topic. When measuring greenhouse gas emissions, the phrase "kg CO_2 equivalent" refers to a standard unit that quantifies the potential for global warming of different greenhouse gases in terms of carbon dioxide (CO_2).

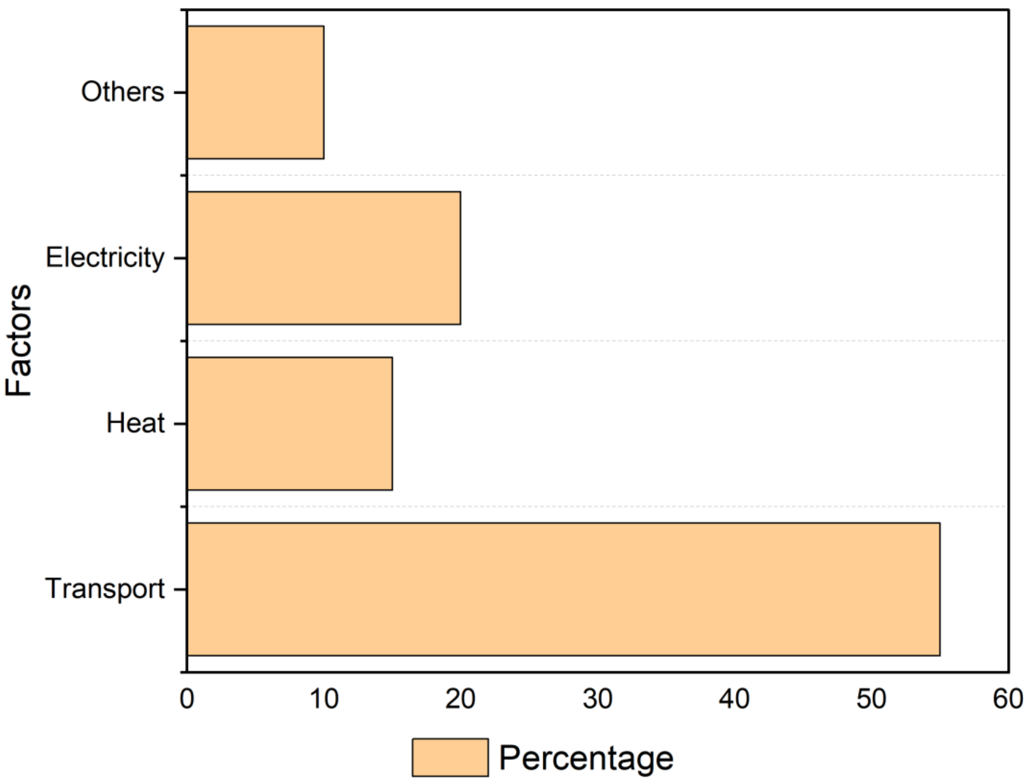

Figure 4.8 Various factors and the corresponding % kg CO_2 equivalent by ReCiPe 2016

The **Figure 4.8** corresponds to the relationship between transport, electricity, heat, and other various factors with the percentage of kg CO_2 equivalent. This analysis has been conducted for the transportation distance between the harvest area and the anaerobic digestion plant of 100 km. From the **Figure 4.8**, nearly 55% of the cause is happened through transport, which is followed by electricity and heat with 20% and 15% respectively.

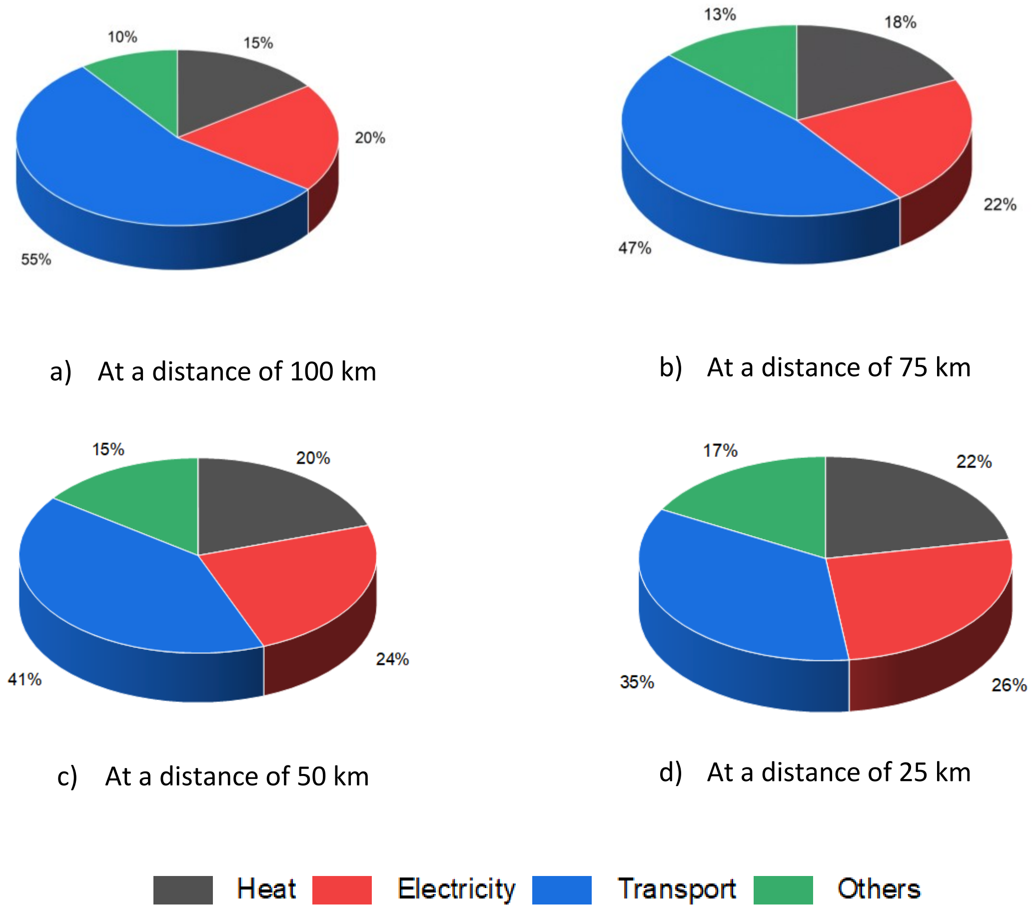

Figure 4.9 Breakdown of CO_2 contributions based on four distinct transportation distances

Figure 4.9(a) represents the proportion of kg CO_2 equivalent of several components at the 100 km transportation distance between the harvest region and the facility. According to ReCiPe 2016 method, transport accounts for around 55% of the kg CO_2 generated. Comparably, the distances showed in Figures 4.9(b), 4.9(c), and 4.9(d) are 75 km, 50 km, and 25 km, respectively. These distances were between the harvest area and facility centre.

Approximately 47%, 41%, and 35% of the kg CO_2 generated by transportation comes from the 75 km, 50 km, and 25 km findings obtained using ReCiPe 2016. The outcome makes it abundantly evident that a shorter transportation distance corresponds to less greenhouse gas emissions. Therefore, 35% of the kg CO_2 equivalent is present if the distance is 25 km. Consequently, if the distance is shortened from 100 km to 25 km, there will be an approximately 36% reduction in kg CO_2 equivalent.

In summary, a key tactic for supply chain networks looking to reduce their environmental impact is the optimisation of transit distance. Electric trucks provide a cleaner and more sustainable form of transportation due to their inherent efficiency and the possibility of using renewable energy sources to power them. This transition is essential to lowering the global carbon footprint, which supports international initiatives to mitigate the negative effects of climate change and promote environmental responsibility in the future. As a result, the network's shorter journey with the implementation of electric truck has a less effect on global warming.

Chapter 5 Summary, Conclusions and Recommendations

5.1 Summary

The initial phase of the project involved evaluating the sustainability of wheat straw across multiple disposal methods, including anaerobic digestion, pyrolysis, gasification, and composting. The most effective method was further scrutinized using SimaPro software, a Life Cycle Assessment tool, with anaerobic digestion proving to be the most favourable method. Anaerobic digestion enhances the environment by efficiently treating wheat straw, mitigating emissions associated with its decomposition, and concurrently producing biogas, a renewable energy source. This sustainable approach minimizes environmental impact, fostering a healthier ecosystem and contributing to overall environmental well-being. Methane is a strong greenhouse gas that would normally be emitted during the natural breakdown of organic materials. Anaerobic digestion has the major advantage of capturing this gas, which reduces methane emissions. Methane emissions are lessened when wheat straw is converted into biogas by anaerobic digestion since the gas is collected and utilised as a fuel source. Subsequently, a social impact analysis was carried out for all four techniques to assess potential damages. Finally, supply chain optimization was implemented to identify various strategies for enhancing the overall network efficiency of converting the wheat straw into biogas along with the selection of which truck is best for transporting the wheat straw from harvest area to the conversion facility.

5.2 Conclusions

The main purpose of this study is to evaluate several methods of disposing of wheat straw, such as gasification, pyrolysis, anaerobic digestion, and composting, to identify the best approach. Anaerobic digestion is the least harmful choice in terms of the environment and has the least effect on global warming when compared to other disposal options. The conversion of wheat straw into biogas through anaerobic digestion can lead to a reduction in fossil fuel consumption for energy production, resulting in lower carbon dioxide (CO_2) emissions compared to conventional energy sources. This has been demonstrated by applying Life Cycle Assessment techniques using SimaPro software.

The next step of the analysis is to optimise the supply chain network such that wheat straw may be converted into biogas through anaerobic digestion. Anaerobic digestion was analyzed because it possesses least environmental damage impact than other techniques from the results through SimaPro software. An environmentally benign energy source called biogas is produced when organic matter breaks down anaerobically. The next phase includes the supply chain of transferring the wheat straw from the harvest area to anaerobic digestion centre through the truck. First, the traditional supply chain model is examined, and then it is contrasted with the possible conversion of conventional fuel vehicles into electric trucks. The results highlight the benefits of adopting electric vehicles over conventional ones in terms of sustainability of the economy and environment. This study demonstrates the promise of novel agricultural residue management approaches for waste-to-resource conversion, emission reduction, and energy generation.

5.3 Limitations and uncertainties of the study

- ✓ Potential changes in market dynamics, technological improvements, or policy changes that could impact the sustainability and feasibility of wheat straw disposal methods and supply chain optimisation tactics in the future are not fully considered in this study. Long-term sustainability assessments grow challenging due to the anticipation of eventual changes.
- ✓ Limited availability of high-quality data posed a challenge in accurately assessing the sustainability implications of wheat straw utilization.

- ✓ Supply chain optimisation and disposal technique evaluations are predicated on research and assumption. Since these assumptions may not accurately reflect the intricacies of real-world situations, the analysis's accuracy is dependent on them. Some of the assumptions encompass transportation distances, waste composition and costs.
- ✓ The interactions between different components of the wheat straw supply chain, waste disposal methods, and emissions reduction strategies are complex and multifaceted, introducing uncertainties into possible analyses.

5.4 Recommendations for future research

Based on the results of this study, the following recommendations are proposed for future research:

- ✓ The development of an innovative supply chain structure aims to improve several areas, with a particular emphasis on reducing environmental impact. To reduce transportation needs and reduce the amount of CO_2 released into the atmosphere, the creative model might be modified to incorporate the building of an anaerobic plant at or very near the harvest location.

- ✓ The application of internet of things (IoT) can be incorporated such that the sustainability of agricultural biomass residue such as wheat straw from the standpoints of supply chain management, residue disposal, and emissions reduction, are appropriately evaluated. The real time monitoring of transportation and environmental monitoring on emission reduction would be some of the main metrics of IoT.

- ✓ To examine the forthcoming primary crop residue in agriculture, specifically corn stover, and forecast its environmental consequences, ultimately arriving at a conclusion or statement regarding which residue exhibits a greater impact on environment.

- ✓ To determine the least harmful method for the environment by looking at several ways to turn wheat straw into useful goods and comparing the results with the current study.
- ✓ Future research efforts should focus on collecting more comprehensive and reliable data to enhance the accuracy of sustainability assessments.
- ✓ Responsible utilization of crop residues for energy production can help decrease greenhouse gas emissions and combat global warming.
- ✓ Effective collaboration among governments, farmers, researchers, and industries is vital to tackle the challenges of global warming and its impact on agriculture.

Bibliography

Alsamaq, S., Kingdom, C., & Garba, N. A. (2015). Life cycle assessment of agricultural residues utilization for biogas deployment. *WEENTECH Proceedings in Energy GCESD 2015 24th-26th February 2015 Technology Park, Coventry University Coventry, United Kingdom*, *24*(26), 159.

Barton, R. (2006). Estimation of costs of heavy vehicle use per vehicle-kilometre in Canada. *Transportation Canada Economic Analysis Directorate, File T8080-05*, *326*.

Baruah, D., & Baruah, D. C. (2014). Modeling of biomass gasification: A review. *Renewable and Sustainable Energy Reviews*, *39*, 806-815.

Battais, F., Richard, C., Jacquenet, S., Denery-Papini, S., & Moneret-Vautrin, D. A. (2008). Wheat grain allergies: An update on wheat allergens. *European Annals of Allergy and Clinical Immunology*, 40(3), 67.

Biswas, B., Pandey, N., Bisht, Y., Singh, R., Kumar, J., & Bhaskar, T. (2017). Pyrolysis of agricultural biomass residues: Comparative study of corn cob, wheat straw, rice straw and rice husk. *Bioresource Technology*, *237*, 57-63.

Chew, K. W., Chia, S. R., Yen, H. W., Nomanbhay, S., Ho, Y. C., & Show, P. L. (2019). Transformation of biomass waste into sustainable organic fertilizers. *Sustainability*, *11*(8), 2266.

Christensen, T. H., Damgaard, A., Levis, J., Zhao, Y., Björklund, A., Arena, U., Barlaz, M. A., Starostina, V., Boldrin, A., Astrup, T. F., & Bisinella, V. (2020). Application of LCA modelling in integrated waste management. *Waste Management*, 118, 313-322.

Cooper, S., Duchesne, L. C., & Laporte, M. F. (2006). Forests as a source of bioproducts. *Bioproducts from Canada's Forests: New Partnerships in the Bioeconomy*. Springer, Dordrecht, The Netherlands, pp. 1-33.

Cooperband, L. (2002). The art and science of composting. *Center for Integrated Agricultural Systems*.

Danca, A. C. (2005). SWOT analysis. A*vailable at: website–www. stfrancis. edu*.

Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., & Finnveden, G. (2007). What life-cycle assessment does and does not do in assessments of waste management. *Waste Management*, *27*(8), 989-996.

El-Ramady, H., El-Henawy, A., Amer, M., Omara, A. E. D., Elsakhawy, T., Elbasiouny, H., Elbehiry, F., Abou Elyazid, D., & El-Mahrouk, M. (2020). Agricultural waste and its nano-management: Mini review. *Egyptian Journal of Soil Science*, 60(4), 349-364.

Energyhub.org. (2024). Canada's Clean Energy Reference Source. Retrieved January 20, 2024, from https://www.energyhub.org.

Environment Canada. (2002). Canada's Greenhouse Gas Inventory Fact Sheet 1- Overview: 1990-2000. Retrieved December 11, 2023, from http://www.ec.gc.ca/pdb/ghg/1990_00_factsheet/fs1_e.cfm-agriculture.

Ghinea, C., Petraru, M., Simion, I. M., Bressers, D. S. H. T. A., & Gavrilescu, M. (2014). Life cycle assessment of waste management and recycled paper systems. *Environmental Engineering & Management Journal*, *13*(8), 2073-2085.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. *A Life Cycle Impact Assessment Method which comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level (First edition).* Ministry of Housing, Spatial Planning and Environment, The Netherlands.

Gontard, N., Sonesson, U., Birkved, M., Majone, M., Bolzonella, D., Celli, A., AngellierCoussy, H., Jang, G. W., Verniquet, A., Broeze, J., Schaer, B., Batista, A. P., & Sebok, A., (2018). A research challenge vision regarding management of agricultural waste in a circular bio-based economy. *Critical Reviews in Environmental Science and Technology*, 48, 614–654.

Government of Canada. (2018). Canada Open Government Portal: Open Data. Retrieved November 25, 2023, from https://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9/resource/5c125460-2cd7-4264-a6e7-2ef49521295c.

Harshwardhan, K., and Upadhyay, K. (2017). Effective utilization of agricultural waste: Review. *Journal of Fundamentals of Renewable Energy and Applications*, 7(5), 52–59, 2017.

Hewson, D. (2010). Assessment of agricultural residuals as a biomass fuel for Ontario power generation. The Scientific and Technical Information, U.S. Department of Energy.

Hiloidhari, M., Baruah, D. C., Singh, A., Kataki, S., Medhi, K., Kumari, S., Ramachandra, T. V., Jenkins, B. M., & Thakur, I. S. (2017). Emerging role of geographical information system (GIS), Life Cycle Assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning. *Bioresource Technology*, *242*, 218-226.

Jones, H. D. (2005). Wheat transformation: current technology and applications to grain development and composition. *Journal of Cereal Science*, *41*(2), 137-147.

Joshi, V. K. (2020). Fruit and vegetable processing waste management–An overview. *International Journal of Food and Fermentation Technology*, *10*(2), 67-94.

Koopmans, A., & Koppejan, J. (1997). Agricultural and forest residues-generation, utilization, and availability. *Regional Consultation on Modern Applications of Biomass Energy*, *6*, 10.

Koua, B. K., Zinla, D. B. T., Koffi, P. M. E., & Gbaha, P. (2022). Assessment of the energy potential of agricultural crop residues in rural areas of Côte d'Ivoire. *Biomass Conversion and Biorefinery*, 13, 10215–10228.

Kung, C. C., Kong, F., & Choi, Y. (2015). Pyrolysis and biochar potential using crop residues and agricultural wastes in China. *Ecological Indicators*, *51*, 139-145.

Laiq Ur Rehman, M., Iqbal, A., Chang, C. C., Li, W., & Ju, M. (2019). Anaerobic digestion. *Water Environment Research*, *91*(10), 1253-1271.

Li, X., Mupondwa, E., Panigrahi, S., Tabil, L., Sokhansanj, S., & Stumborg, M. (2012). A review of agricultural crop residue supply in Canada for cellulosic ethanol production. *Renewable and Sustainable Energy Reviews*, *16*(5), 2954-2965.

Liimatainen, H., van Vliet, O., & Aplyn, D. (2019). The potential of electric trucks–An international commodity-level analysis. *Applied Energy*, *236*, 804-814.

Luttenberger, L. R. (2020). Waste management challenges in transition to circular economy–Case of Croatia. *Journal of Cleaner Production*, *256*, 120495.

McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresource Technology*, *83*(1), 37-46.

Menoufi, K. A. I. (2011). Life Cycle Analysis and Life Cyle Impact Assessment methodologies: A state of the art.

Nguyen, T. L. T., Hermansen, J. E., & Nielsen, R. G. (2013). Environmental assessment of gasification technology for biomass conversion to energy in comparison with other alternatives: The case of wheat straw. *Journal of Cleaner Production*, *53*, 138-148.

Obi, F. O., Ugwuishiwu, B. O., & Nwakaire, J. N. (2016). Agricultural waste concept, generation, utilization and management. *Nigerian Journal of Technology*, *35*(4), 957-964.

Pergola, M., Persiani, A., Pastore, V., Palese, A. M., D'Adamo, C., De Falco, E., & Celano, G. (2020). Sustainability assessment of the green compost production chain from agricultural waste: A case study in southern Italy. *Agronomy*, *10*(2), 230.

Prasad, N. L., Sri, P. U., Vizayakumar, K., & Srikanth, R. (2021). Performance analysis of a conventional and renewable energy based electric power generation systems–A comparative LCA study. *IOP Conference Series: Materials Science and Engineering*, 1057, 12054.

Racz, L., Fozer, D., Nagy, T., Toth, A. J., Haaz, E., Tarjani, J. A., Andre, A., Selim, A., Valentinyi, N., & Mika, L. T. (2018). Extensive comparison of biodiesel production alternatives with life cycle, PESTLE and multi-criteria decision analyses. *Clean Technologies and Environmental Policy*, 20, 2013-2024.

Rakkar, M. K., & Blanco-Canqui, H. (2018). Grazing of crop residues: Impacts on soils and crop production. *Agriculture, Ecosystems & Environment*, *258*, 71-90.

Ramdas, S., Singh, R., & Sharma, I. (2012). Exploring the performance of wheat production in India. *Journal of Wheat Research*, *4*(2), 37-44.

Rathore, D., Pant, D., & Singh, A. (2013). A comparison of life cycle assessment studies of different biofuels. In *Life Cycle Assessment of Renewable Energy Sources* (pp. 269-289).

Renault Trucks. (2018). Renault Trucks unveils its second-generation electric trucks [Web page]. Retrieved January 3, 2024, from https://www.renault-trucks.com/en/newsroom/press-releases/renault-trucks-unveils-its-second-generation-electric-trucks-complete-ze.

Rodrigue, J. P., Slack, B., & Comtois, C. (2017). Green logistics. In *Handbook of logistics and supply-chain management* (Vol. 2, pp. 339-350). Emerald Group Publishing Limited.

SETAC. (1993). Guidelines for Life Cycle Assessment: A Code of Practice. Society of Environmental Toxicology and Chemistry.

Ruiz, H. A., Silva, D. P., Ruzene, D. S., Lima, L. F., Vicente, A. A., & Teixeira, J. A. (2012). Bioethanol production from hydrothermal pretreated wheat straw by a flocculating Saccharomyces cerevisiae strain–Effect of process conditions. *Fuel*, *95*, 528-536.

Shafie, S. M., Mahlia, T. M. I., Masjuki, H. H., & Ahmad-Yazid, A. (2012). A review on electricity generation based on biomass residue in Malaysia. *Renewable and Sustainable Energy Reviews*, *16*(8), 5879-5889.

Singh, H., Singh, A. K., Kushwaha, H. L., & Singh, A. (2007). Energy consumption pattern of wheat production in India. *Energy*, *32*(10), 1848-1854.

Statistics Canada. (2023). Canada Outlook: Principal Field Crops 2023 [Webpage]. Agriculture and Agri-Food Canada. Retrieved January 21, 2024, from https://agriculture.canada.ca/en/sector/crops/reports-statistics/canada-outlook-principal-field-crops-2023-11-21.

Talebnia, F., Karakashev, D., & Angelidaki, I. (2010). Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation. *Bioresource Technology*, *101*(13), 4744-4753.

Timbers, G. E., & Downing, C. G. E. (1977). Agricultural biomass wastes: Utilization routes. *Canadian Agricultural Engineering*, *19*(2), 84-87.

Tsai, W. T., Chang, C. Y., Wang, S. Y., Chang, C. F., Chien, S. F., & Sun, H. F. (2001). Cleaner production of carbon adsorbents by utilizing agricultural waste corn cob. *Resources, Conservation and Recycling*, *32*(1), 43-53.

Veracoechea D'Urso, L. S. (2023). Life cycle assessment of wheat straw and corn stover biomass for the production of biochar applied in Saxony's agriculture.

Zheng, Y., & Qiu, F. (2020). Bioenergy in the Canadian Prairies: Assessment of accessible biomass from agricultural crop residues and identification of potential biorefinery sites. *Biomass and Bioenergy*, *140*, 105669.