Techno-economic assessment of biofuels production from sugarcane bagasse

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By

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Preface

The candidate conducted the research presented in this dissertation under the guidance of Prof. M. Chetty and Prof. A.H. Mohammadi, while affiliated with the Discipline of Chemical Engineering in the Faculty of Engineering and the Built Environment at Durban University of Technology, located in Durban, South Africa.

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Declaration

I, the undersigned, Ayanda Siphumelele Buthelezi (21556110), declare that:

i. I am the author of the work contained in this dissertation.
ii. Any work obtained from external sources has been appropriately acknowledged and referenced in the References section of the dissertation.
iii. Everyone who contributed to the successful completion of this project has been acknowledged.
iv. The work presented in this dissertation has not previously been submitted to any other university or examination board for any degree or examination.

Place of Submission: Durban University of Technology

Student: Ayanda Siphumelele Buthelezi

Signature: ……..... Date: 13 February 2026 …….

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Dedication

I would like to dedicate this work to the Almighty, His Holiness Shembe uNyazilwezulu, my great-grand ancestors, my family, my friends, and my unborn generations.

Executive summary

In tropical countries such as South Africa, sugarcane bagasse is one of the most abundant lignocellulosic renewable feedstocks for biofuel production. The adoption of integrated processing routes for utilising by-products is a promising approach for achieving near-complete conversion of organic biomass while reducing waste generation. This study investigates a second-generation sugarcane bagasse biorefinery annexed to a sugar mill. A techno-economic assessment approach was adopted to determine the feasibility of each investigated process route. Five sugarcane bagasse-to-biofuel conversion routes were evaluated, namely the bioethanol fermentation process, the anaerobic digestion process, the dark fermentation process, the gasification process, and the fast pyrolysis process. Each process route was simulated individually in Aspen Plus V11 using input data obtained from literature sources. The simulations generated mass and energy balances, which were subsequently utilised for techno-economic analyses (TEA) and life cycle assessments (LCA). The TEA was performed using Aspen Process Economic Analyzer (APEA) and Microsoft Excel spreadsheets, while the LCA was conducted using SimaPro software.

The study considered a typical sugar mill located at Sezela in KwaZulu-Natal, South Africa, with a cane crushing capacity of 300 tonnes of sugarcane per hour, producing approximately 81 tonnes of sugarcane bagasse per hour. It was assumed that 36% of the bagasse is utilised in boilers for steam generation. The remaining portion (51.84 tonnes per hour) was allocated to the biorefinery, which was assumed to be annexed to the sugar mill. This configuration eliminates transportation costs and minimises feedstock costs.

Following the completion of process simulations in Aspen Plus, Aspen Process Economic Analyzer was used to estimate the installed equipment costs for each investigated process route. The installed equipment costs were escalated from a 2019 base year, consistent with Aspen V11 cost correlations, to 2024 values using the Chemical Engineering Plant Cost Index (CEPCI). Capital expenditure (CAPEX) for each process route was estimated using the installed equipment costs. Variable operating costs (VOC) and fixed operating costs (FOC) were combined to determine the operating expenditure (OPEX) of each biorefinery. It was assumed that the plant operates for 5000 hours per year. Total sales revenue was calculated based on the sales of valuable final products, and selling prices were obtained from literature sources and online market prices. Discounted cash flow analysis was used to evaluate the

economic performance of each process route, assuming a tax rate of 28%, a discount rate of 12%, and straight-line depreciation over 5 years at 20% per year. The plant lifetime was assumed to be 25 years. Four economic indicators were calculated, namely net present value (NPV), payback period (PBP), return on investment (ROI), and profitability index (PI).

Life cycle assessment (LCA) was conducted to evaluate the environmental impacts of the investigated process routes. SimaPro software was used for the LCA, following ISO 14040 and ISO 14044 methodology. The ISO framework includes four main stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results. The goal and scope of the LCA were to determine the least environmentally impactful processing route using a cradle-to-gate system boundary. The LCI was based on mass and energy balances obtained from Aspen Plus simulations, and the Ecoinvent database in SimaPro was utilised. The LCIA was performed using two approaches. The first was damage assessment, which applied the ReCiPe 2016 Endpoint (H) method and evaluated three damage categories, namely human health, ecosystems, and resources. The second approach was characterisation, which applied the ReCiPe 2016 Midpoint (H) method. Under the midpoint approach, eight impact categories were evaluated, including global warming, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, mineral resource scarcity, fossil resource scarcity, and water consumption.

The fast pyrolysis process was identified as the most profitable process route, achieving an NPV of 199.44 million USD, a payback period of 1 year, an ROI of 10.27, and a PI of 46.64. The dark fermentation process ranked second, with an NPV of 67.41 million USD, a payback period of 3.3 years, an ROI of 1.51, and a PI of 7.95. The gasification process ranked third, with an NPV of 23.21 million USD, a payback period of 3.6 years, an ROI of 1.40, and a PI of 7.31. The anaerobic digestion process ranked fourth, with an NPV of 37.57 million USD, a payback period of 4.4 years, an ROI of 1.16, and a PI of 5.85. Under the conditions assumed in this study, the bioethanol fermentation process was economically unfeasible, as it produced a negative NPV, indicating that the project would not recover its initial investment by the end of the plant lifetime.

The life cycle assessment results showed that the dark fermentation process was the most environmentally favourable process route, followed by the fast pyrolysis process, anaerobic digestion process, gasification process, and bioethanol fermentation process, respectively. The

bioethanol fermentation process showed the highest environmental impacts across all evaluated impact categories, making it the least environmentally favourable processing route. Electricity was used as the energy source in the LCA, and energy consumption significantly influenced environmental impacts. Since South African electricity is largely generated from coal, process routes with high energy demand exhibited higher environmental impacts and were therefore less environmentally sustainable.

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Keywords

Aspen Plus simulations

Biomass

Biofuels

Life Cycle Assessment (LCA)

SimaPro simulations

Sugarcane bagasse

Techno-Economic Assessment (TEA)

Abbreviations List

Abbreviation	Description
1G	First-generation biofuels
2G	Second-generation biofuels
AD	Anaerobic digestion
APEA	Aspen process economic analyser
CAPEX	Capital and expenditure
CC	Contingency costs
CEPCI	Chemical engineering plant cost index
CHP	Combined heat and power
DCFA	Discounted cash flow analysis
DF	Dark fermentation
DM	Dry matter
EC	Engineering cost
EPD	Environmental product declarations
FOC	Fixed operating costs
HHV	Higher heating value
HPWS	High-pressure water scrubbing
HRT	Hydraulic retention time
HTL	Hydrothermal liquefaction
IRR	Internal rate of return
ISBL	Inside battery limits
ISO	International organisation for standardisation
LC	Labour costs
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle Impact assessment
LHW	Liquid hot water
MEA	Monoethanolamine
NPV	Net present value
NREL	National renewable energy laboratory
OLR	Organic loading rate
OPEX	Operating expenses
OSBL	Outside battery limits
PAHs	Polycyclic aromatic hydrocarbons
PBP	Payback period
PI	Profitability Index
REIPPPP	Renewable energy independent power producer procurement program

Abbreviation	Description
ROI	Rate of return on investment
SASA	South African sugar association
SCB	Sugarcane bagasse
SDG	Sustainable development goals
SHF	Separate hydrolysis and fermentation
SCOAs	Short-chain organic acids
SSCF	Simultaneous saccharification and co-fermentation
SSF	Simultaneous saccharification and fermentation
SUC	Startup costs
TEA	Techno-economic assessment
USD	United States dollar
VFA	Volatile fatty acids
VOC	Variable operating costs
WC	Working capital

Chapter 1: INTRODUCTION

1.1. Background

The Production and utilisation of renewable energy resources nationally and globally are driven by the combined effects of climate change, the continuous increase in fossil fuel prices, and the progressive depletion of fossil fuel resources in the world (Clomburg, Crumbley, and Gonzalez 2017); Twidell (2021). The energy consumption is also increasing; more ways to produce energy need to be investigated. This leads to the shift toward alternative renewable energy resources. There is a foreseeable potential for biofuels to serve as an environmentally friendly source of power, heat, energy, and motor fuel. This has the capacity to make a substantial contribution towards sustainable development, addressing both socioeconomic and environmental challenges (Onthong and Juntarachat 2017).

Biofuel refers to a type of fuel that is obtained from various sources, such as biomass, including algae material, vegetation, animal waste, or agricultural waste. Agricultural waste refers to the undesirable byproducts generated as a result of agricultural practices and other activities that involve the use of agricultural materials. This includes agricultural residues and industrial residues. The issue of agricultural waste has attracted growing attention in recent years due to its potential to generate substantial environmental challenges. Sugarcane is a highly cultivated agricultural commodity worldwide, with significant production occurring in tropical regions (Bordonal *et al.* 2018). The accumulation of substantial amounts of agricultural waste leads to greenhouse gas emissions and the release of harmful gases, which can result in public health problems as well as environmental impacts (Elbasiouny *et al.* 2020). Agricultural waste consequences highlighted above enlighten the importance of utilisation of agricultural wastes as a renewable energy source to overcome environmental damages and energy crisis problems (Martinez-Hernandez *et al.* 2018).

Prominent sugarcane-growing nations include Brazil, India, China, Thailand, Pakistan, and Mexico. Sugarcane is widely used in sugar production, resulting in sugarcane bagasse (SCB) as the byproduct. SCB is classified as industrial agricultural waste and has significant potential to be used in the production of biofuels as the feedstock (Talukdar *et al.* 2017; Zafeer *et al.* 2023). This study will focus on biofuels produced from sugarcane bagasse.

Sugarcane bagasse (SCB) refers to the fibrous residue that remains after the extraction of juice from sugarcane stalks. Sugar content is extracted from crushed sugarcane, and the remaining byproduct is sugarcane bagasse, which releases a higher heating value (HHV) of about 19.25MJ/kg (Athira, Bahurudeen, and Appari 2021). Approximately 1.25 kilograms of bagasse is generated per kilogram of sugar (Sahu 2018). According to the South African Sugar Association (SASA), South Africa's annual sugarcane production capacity is at 20 million tonnes, which results in approximately three million tonnes of dry bagasse produced on average, with one-third of it being surplus to industry requirements. Surplus SCB is currently utilised for furfural, paper milling, and cogeneration, although large volumes remain unused. Bagasse is used to meet 75% to 90% of the energy needs of sugarcane manufacturing companies.

The process of burning SCB in boilers is employed to fulfil the energy demands of the sugar mill. SCB is typically combusted in boilers with low efficiency (Mandegari, Farzad, and Görgens 2017). The utilisation of surplus bagasse to produce biofuel, steam, and power can be facilitated through the enhancement of the Combined Heat and Power (CHP) plant. This can be achieved by substituting low-pressure boilers with more efficient high-pressure boilers, thereby enabling energy self-sufficiency in the facilities.

High gaseous emissions released by bagasse-fired boilers have been reported to increase the risk of respiratory infections, reduce immune system function, and contribute to pulmonary disease (Tomlin 2021).In the global trend toward increased use of renewable feedstocks, sugarcane has become an increasingly important crop. SCB is one of the most promising lignocellulosic materials for cost-effective biofuel production due to its relative abundance, potential lower supply costs, and it does not compete for land with food crops. There are four generations of biofuels, which are primarily classified based on the type of feedstock used and the production pathway.

First-generation biofuels are produced from planted crops like sugarcane, while non-food plants, like lignocellulosic biomass, are used to produce second-generation biofuels (Sindhu *et al.* 2019). Third-generation biofuels are derived from algae. Fourth-generation biofuels represent an advanced category that integrates biofuel production with carbon capture and storage (CCS) or genetic modification of biomass to achieve carbon-negative or near-zero

greenhouse gas emissions, thereby addressing both energy production and climate change mitigation (Aro 2016; Abdullah *et al.* 2019).

Bio-refinery feedstocks have been extensively researched (Onthong and Juntarachat 2017), while some studies were previously conducted with respect to biochemicals production and renewable resource biopolymers (Anju, Binod, and Pandey 2017). An important decision-making stage in the development of the bio-derived economy is the technological and economic investigation of various biofuels and biochemical technologies. Economic and environmental analyses of bagasse energy utilisation require further research. Bagasse is considered a second-generation feedstock for the generation of biofuels. Apart from water and sugars, the sugarcane plant contains lignocellulosic components which could be employed as a raw material for biofuels production through biochemical or thermochemical conversion processes (Nogueira, Kang, and Skeer 2019).

SCB is abundant worldwide. Because of its abundance in nature, it has been studied for a variety of purposes, including its use for a sustainable environment. The chemical makeup of SCB makes it a suitable feedstock for a variety of processes. Sugarcane bagasse compositions are shown in Table 1-1.

Table 1-1: Sugarcane Bagasse Compositions (Mandegari, Farzad and Görgens 2017)

Component	**Composition (mass %)**
Cellulose	41.1
Hemicellulose	26.4
Lignin	21.7
Ashes	4
Extractive	6.8

There are three major technology categories used to transform biomass into green, sustainable goods, namely biochemical conversions, thermochemical conversions, and physicochemical conversions. Thermal techniques widely utilised for biomass conversion to fuel are pyrolysis, gasification, charcoal, and liquefaction. Anaerobic digestion (AD) and Fermentation are biochemical techniques widely utilised for energy production. Physicochemical conversions include mechanical extraction, separation, and transesterification (Issa *et al.* 2020).

Fermentation is the process through which microbes digest plant sugar and generate ethanol, butanol, and other by-products. Bioethanol is the most researched biofuel among others.

Traditional ethanol production employs sugar crops. However, other resources including lignocellulosic material and starchy plants, can be employed. The fermentation process is commonly conducted under ambient temperature and pressure conditions, in the presence of microorganisms. During fermentation, the bioethanol content ranges between 10% and 18% by volume (Ahmed *et al.* 2017).

Pre-treatment, hydrolysis, fermentation, and distillation are key processes in the conversion of sugarcane bagasse to bioethanol. Bioethanol is a type of renewable energy that is commonly used as a motor fuel and is also used to enhance the quality of gasoline. Bioethanol may be combined with gasoline in any ratio, and all existing gasoline engines in vehicles can run with ethanol mixtures of up to 10% (Konde *et al.* 2021).

Biogas can be produced through Anaerobic digestion (AD). Bio-methanation is a process whereby organic matter is degraded by micro biochemical activity in the absence of oxygen (Bharathiraja *et al.* 2018). Biogas is an environmentally sustainable energy source that is presently being employed in numerous developing countries as a viable and renewable alternative for a wide range of applications. Numerous countries are currently engaged in the development of legislative frameworks aimed at regulating the biogas industry. Biogas is seen as the renewable and ecological energy of the future (Issa *et al.* 2020).

Biogas is a fuel that possesses numerous ecological benefits, as it is both renewable and clean. It is produced within digesters that are filled with feedstock. Additionally, biogas is an inexpensive fuel option that offers high-quality performance and exhibits flexibility in its usage. It is commonly acknowledged as a viable alternative renewable energy source. According to Ngan *et al.* (2020), this particular resource has the potential to be utilised for various energy applications, such as heat generation, combined heat and power (CHP) systems, or even as a fuel source for vehicles. The adoption of anaerobic digestion (AD) for the treatment of various waste materials, energy plants, and byproducts is increasingly being recognized as a viable approach to mitigate greenhouse gas emissions and enhance the sustainable expansion of energy resources in the long run. The utilisation of anaerobic digestion has become a well-established technique that is extensively utilised for the purpose of stabilising various types of waste, including water treatment residues, industrial wastewater, solid waste, animal manure, etc (Treichel and Fongaro 2019).

Anaerobic digestion is widely regarded as a cost-effective and environmentally sustainable waste treatment method that effectively mitigates the release of greenhouse gases. In addition, it serves to stabilise and reduce the amount of waste produced. A notable benefit of anaerobic digestion is its ability to effectively process a diverse range of organic substrates. Biogas can be used for heat and electricity generation, or alternatively, it can undergo refinement processes to be employed as a fuel source for vehicles within the transportation sector. Moreover, the residual digestate is utilised as a valuable fertiliser for application on agricultural fields (Meisam 2018).

The significance of advancing clean alternative energy sources has been amplified due to the recent energy crisis and escalating apprehension regarding climate change. Biohydrogen derived from cellulosic feedstock, specifically second-generation feedstock (lignocellulosic biomass) and third-generation feedstock (microalgae with high carbohydrate content), exhibits significant potential as a viable solution to address forthcoming energy demands. This alternative energy source possesses several desirable attributes, including its environmentally friendly nature, as it is both clean and CO_2-neutral, and its ability to operate with high efficiency, while minimizing pollution (Twidell 2021). The production of biohydrogen is achieved through the process of fermenting sugars. Bacterial organisms have the capability to undergo fermentation processes using renewable materials, either in the presence of light (known as photo fermentation) or in the absence of light (referred to as dark fermentation)(Hitam and Jalil 2020).

Hydrogen has shown tremendous promise as a future alternative fuel. The hydrogen generation technique has received a lot of interest in recent decades due to its benefits, including its favourable characteristics, such as high conversion efficiency, potential for reuse, and minimal environmental impact. In recent decades, biochemical hydrogen generation has shown considerable potential in addressing the escalating global energy demands by providing a sustainable and substantial source of energy. Extensive research and analysis have been conducted on a variety of microorganisms, specifically bacteria, cyanobacteria, and algae, which possess the ability to produce hydrogen through the utilisation of water, solar energy, and various organic substrates (Hitam and Jalil 2020).

Pyrolysis is a highly promising methodology for the conversion of biomass into biofuel, achieved through the application of elevated temperatures (ranging from 250 to 600 °C) within

an inert environment. The utilisation of pyrolysis technology for the production of bio-based fuels and chemicals from biomass represents a novel approach (Chong *et al.* 2019). The byproducts derived from the process of biomass pyrolysis encompass bio-oil, biochar, and syngas. These outputs possess notable attributes, including environmental sustainability, cost-effectiveness, and biodegradability, rendering them suitable for various applications, particularly energy generation.

The process of sugarcane bagasse gasification plays a significant role in the advancement of sustainable and renewable energy resources. Gasification is a thermochemical conversion process that transforms carbonaceous, organic, or fossil-based substances into a mixture of carbon monoxide, hydrogen, methane, and carbon dioxide. This process involves heating the substance to elevated temperatures, typically in the range of 700-1000°C, while introducing a limited amount of steam, oxygen, or both. The syngas produced has a heating value that ranges from 4 to 6 MJ/kg. The utilisation of bagasse clean syngas in stationary gas turbines is a viable option. Gasification offers the advantage of potentially achieving higher efficiency compared to the direct combustion of the primary fuel. This is due to the ability to combust the fuel at higher temperatures or even in fuel cells, thereby surpassing Carnot's rule on the thermodynamic upper limit of efficiency. According to Veiga and Romanelli (2020), the process of gasification of sugarcane bagasse results in the emission of an equivalent amount of carbon dioxide (CO_2) as it absorbs during its growth, thereby achieving carbon neutrality.

1.2. Problem statement

Rising carbon dioxide (CO2) concentrations and global greenhouse gas emissions resulting from fossil fuel combustion are causing global climate destabilisation, potentially causing irreversible damage to the environment and human well-being (Tangney 2020). Climate change causes direct, indirect, intermediate, and synergistic deaths, including heatwaves, crop failures, droughts, flooding, wildfires, and rising sea levels, thereby increasing global hunger and starvation (Ripple *et al.* 2017; Pearce and Parncutt 2023). Global warming and greenhouse gas emissions are largely caused by fossil fuels (Mohajan 2011; Yoro and Daramola 2020). Fossil fuel resources are non-renewable, and their availability is limited, with depletion approaching due to excessive exploitation. Based on analyses, it has been determined that the extraction rate of global oil resources is approximately four billion tonnes annually. If the

current rate of exploitation of known oil reserves persists or increases, it is projected that all reserves could be depleted within the next four decades (Kalak 2023).

The need to address environmental pollution and the depletion of fossil fuels has prompted efforts to explore energy sources that are environmentally friendly, renewable, and sustainable. The conversion of industrial waste, particularly biomass, has received increasing attention to fulfil the energy demands of human society through the production of biofuels. The utilisation of biomass as an energy source presents favourable environmental characteristics, affordability, and abundant availability (Kalak 2023). Biomass fuels are widely accepted as an interesting fuel type that produces lower net greenhouse gas emissions (Stančin *et al.* 2020; Srivastava *et al.* 2021).

Agricultural and lignocellulosic residues are highly abundant biomass substrates that represent significant sources for the production of biofuels. The global investigation of biofuel production from lignocellulosic biomass derived from agricultural material has been explored(Choudhary *et al.* 2020). The sugarcane industry produces significant quantities of lignocellulosic residues, including bagasse. The utilisation of the complete sugarcane bagasse lignocellulosic biomass for the generation of second-generation (2G) biofuels has the potential to serve as a viable alternative that can contribute to the economic feasibility of the sugar industry while contributing to sustainable energy production (Pereira *et al.* 2015). Literature on techno-economic assessments of sugarcane bagasse biofuels exists but remains limited. Most studies focus on bioethanol, but few compare various processes comprehensively (Hassan, Douglas, and Croiset 2007; Aden and Foust 2009; Mavukwana *et al.* 2013; Baral and Shah 2017; Ravendran, Abdulrazik, and Zailan 2019b; Vasconcelos *et al.* 2020; Aui, Wang, and Mba-Wright 2021; Pan *et al.* 2022). The study aims to contribute to SDG 2030 number 7: Affordable and clean energy.

A Techno-economic assessment of biofuels production from sugarcane bagasse in South Africa aims to address the critical challenge of sustainable energy solutions, economic revitalization, and industrial transition. The recent closure of key petroleum refineries like SAPREF and Engen has left South Africa facing increasing pressure to diversify its energy sources, reduce dependency on fossil fuels, and support the green transition. The closure of these refineries resulted in job losses and energy security concerns, which highlight the urgent need for alternative energy pathways that align with national strategies. One promising solution lies in

the production of biofuels from sugarcane bagasse, which is a lignocellulosic byproduct of the sugar production process.

1.3. Aims and Objectives

Aims:

The primary aim of this study is to evaluate the technological and economic feasibility of biofuel production from sugarcane bagasse, together with the associated environmental impacts assessed through life cycle assessment.

Objectives:

1. To simulate various processing routes for converting sugarcane bagasse into biofuels using Aspen Plus software.
2. To perform an economic assessment of the investigated process routes.
3. To perform a Life Cycle Assessment (LCA) of the investigated process routes.

1.4. Approach

Energy availability is vital for human survival, as most of the human needs are generated using energy, including food and water. Production and utilisation of renewable energy resources, such as sugarcane bagasse, nationally and globally, are driven by the combined effects of climate change and the continuous increase in fossil fuel prices, not to mention the progressive depletion of fossil fuel resources in the world. More sustainable and environmentally friendly energy production techniques not only provide alternative energy sources, but they may also provide environmental benefits, which include waste management and the use of methods that are safe, renewable, and non-toxic with an aim of reducing the environmental impact of production and consumption. The use of renewable energy sources also provides the opportunity of reducing the demand for natural resources and minimising waste, thereby supporting the concept of the circular economy. As a result, this study utilises data from the literature to demonstrate its contribution to two Sustainable Development Goals (SDGs) of the 2030 Agenda, namely SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). The study assesses the utilisation of sugarcane bagasse for the production of biofuels, assessing the technicality, economic viability, and environmental effects of different processing routes.

1.5. Thesis overview

This thesis consists of five chapters, as presented below:

Chapter 1: Chapter one serves to introduce and provide context for the entire investigation, with a particular emphasis on explaining the purpose and significance of the study.

Chapter 2: This chapter provides a detailed literature review. The status of energy sources in South Africa is discussed, together with the use of biofuels as a source of energy. The sugar production process is briefly discussed to demonstrate how sugarcane bagasse is produced. The possible biofuels that can be produced from sugarcane bagasse are discussed, followed by the various processing techniques that can be used for biofuels production from sugarcane bagasse. Other previous Techno-economic Assessment (TEA) studies on the production of biofuels from sugarcane bagasse are briefly discussed.

Chapter 3: This section provides a detailed explanation of the research methodology used for attaining each of the research objectives. The methodology used to simulate the processing routes in Aspen Plus software is presented, together with the methodology for the economic evaluation and environmental assessment, respectively.

Chapter 4: The detailed results gathered from the research and their discussions are presented.

Chapter 5: This chapter presents conclusions and recommendations for the research study.

Chapter 2: LITERATURE REVIEW

2.1. Introduction

Chapter two provides a comprehensive overview of the production of biofuels from sugarcane bagasse, offering an in-depth review of its background and significance. A thorough investigation was conducted to evaluate conversion techniques for sugarcane bagasse to biofuels, which include gasification, pyrolysis, direct combustion, hydrothermal liquefaction, anaerobic digestion, and fermentation, including their operational conditions and limitations. It further provides a brief overview of the sugar production process, which entails how sugarcane bagasse is produced as a byproduct and further explains other processes involved in sugar processing. This chapter is crucial because it focuses on the literature data that will be essential in the study design and evaluation phases.

2.2. Energy in South Africa

Coal-fired power stations in South Africa are responsible for the generation of approximately 85% of the country's total electricity output, which amounts to a substantial 42000 MW. Despite the prevailing environmental concerns, it is anticipated that coal will remain the primary source of power generation in South Africa for the forthcoming decade. However, it is worth noting that renewable energy sources are expected to experience substantial growth and progressively augment their contribution to the overall energy mix. South Africa ranks as the fourteenth most significant contributor to global greenhouse gas emissions and is actively engaged in enhancing its environmental performance. It is anticipated that there would be a recovery in energy consumption after a substantial decrease in 2020 due to the worldwide impact of the COVID-19 pandemic. The recovery was anticipated to occur at an average annual growth rate of 0.3% throughout the forecast period, spanning from 2021 to 2030. The anticipated gradual pace of expansion is projected to reflect improvements in energy efficiency, in conjunction with the ongoing gradual growth of the South African economy (Jiang, Van Fan, and Klemeš 2021; PowerAfrica 2023).

The utilisation of renewable energy is increasingly gaining traction as a favourable power source within the nation. South Africa has implemented the Renewable Energy Independent Power Producer Procurement Program (REIPPPP) to enhance its energy portfolio and entice a

greater number of independent power producers (IPPs) to participate in the sector. This initiative has demonstrated notable efficacy in facilitating the realization of renewable energy ventures for commercial utilisation. The Renewable Energy Independent Power Producer Procurement Program (REIPPPP) has effectively secured a total capacity of 6.4 GW from 112 Independent Power Producers (IPPs) across seven bid windows as of 2023, as reported by Power Africa (PowerAfrica 2023).

2.3. Biofuels

Production and utilisation of renewable energy nationally and globally are driven by the combined effects of global warming, volatility in fossil fuel prices, and the progressive depletion of fossil fuel resources worldwide (Twidell 2021). Energy consumption is also increasing, more ways to produce energy need to be investigated. The evolving trend towards sustainable energy and the energy crisis that occurred after the COVID-19 pandemic serve as more obvious examples of this lesson (Steffen *et al.* 2020; Hoang *et al.* 2021a). This causes a change in favour of renewable energy sources that are an alternative. It is foreseeable that biofuels will play a significant role in sustainable development with regard to socioeconomic and environmental issues, as they could be a potential renewable source of energy (Onthong and Juntarachat 2017).

There are four generations of biofuels, classified according to the type of feedstock used and the production pathway. First-generation biofuels are produced from food crops such as sugarcane and maize; however, their major limitation is the food–fuel trade-off, and many first-generation biofuels exhibit a negative or marginal net energy gain (Darda, Papalas, and Zabaniotou 2019). Second-generation biofuels are derived from non-food biomass, including lignocellulosic materials such as agricultural residues and industrial wastes, and life-cycle assessments have shown a significant improvement in net energy gain compared to first-generation biofuels (Ummalyma *et al.* 2022). Third-generation biofuels are produced from microorganisms and microalgae, which offer high productivity and do not compete for arable land (Sirohi, Choi, and Sim 2022). Fourth-generation biofuels represent an advanced category that integrates biofuel production with technologies such as carbon capture and storage or genetically engineered biomass, with the aim of achieving near-zero or carbon-negative greenhouse gas emissions (Aro 2016; Abdullah *et al.* 2019).

Biofuel is a type of fuel that is produced from biomass, which refers to organic matter such as plant or algae material, animal waste, or agricultural waste. Agricultural waste refers to the undesirable byproducts generated because of various agricultural practices and other activities that include the use of agricultural materials, including agricultural residues and industrial residues. Agricultural waste has become an increasing concern in recent years as it may cause significant environmental problems (Koul, Yakoob, and Shah 2022). The accumulation of large amounts of agricultural waste leads to greenhouse gas emissions and the emission of toxic gases, which lead to public health problems and environmental impact (Elbasiouny *et al.* 2020). The above-mentioned consequences of agricultural waste highlight the importance of the utilisation of agricultural waste as a renewable energy source to overcome environmental damage and energy crisis problems.

A brief overview of energy in South Africa is highlighted in Section 2.2. A brief overview of the sugar production process is presented in 2.4, which entails how sugarcane bagasse is produced as a byproduct and further explains other processes involved in sugar processing. The detailed description of biofuel conversion techniques applicable to this study is presented in section 2.7 of this dissertation.

2.4. Sugar industry

According to Abdool Karim, Kruger, and Hofman (2020), South Africa (SA) possesses the most extensive sugar industry in Africa, making a substantial contribution to the overall economic growth of the nation. Nevertheless, the global sugar industry encounters various obstacles, such as volatile and depressed global sugar prices, competition from cost-effective global sugar manufacturers, escalating energy and agricultural input expenses, and deteriorating infrastructure (Department of Trade, Industry and Competition 2020). These challenges have put forth a proposed solution that involves enhancing the utilisation of second-generation (2G) sugarcane residues to expand the array of products produced by sugar mills (Abdool Karim, Kruger, and Hofman 2020). In the context of South Africa, it has been observed that the production of bagasse amounts to 270-280 kg per tonne of harvested cane. Currently, this bagasse is utilised as boiler fuel in sugar mills, a practice that is deemed inefficient (Kabeyi and Olanrewaju 2023). However, it is worth noting that this inefficient utilisation of bagasse presents an opportunity for the development of a bioethanol market, which has the potential to reach a value of $1.5 billion (Singh *et al.* 2022).

To solve the above-mentioned challenges faced by the sugar industry, a strategy for re-vitalisation of the sugar industry, which is to annex biorefineries to existing sugar mills, is proposed (Mandegari, Farzad, and Görgens 2016; Kaur and Singh 2021). A Biorefinery uses low-value lignocellulosic biomass to produce high-value chemicals, biofuel, and bioenergy (Kapanji, Haigh, and Görgens 2021). These studies examined the sugar industry's proposition to establish a biorefinery as an extension to an already existing sugar mill. The primary objective of this proposed biorefinery was to generate bioethanol and electricity. The results showed that the biorefinery under consideration can achieve energy self-sufficiency. This can be accomplished by diverting 35% of the feedstock directly to the boiler. This process generates sufficient steam and power to meet the energy demands of both the sugar mill and the biorefinery facility (Mandegari, Farzad, and Görgens 2016; Haigh *et al.* 2020).

The exploration of integrating biorefineries with sugar mills for the purpose of ethanol production has been the subject of investigation (Petersen 2012; Mandegari, Farzad, and Görgens 2017). The present study conducted a comparative analysis between second-generation ethanol production from bagasse and trash in a Simultaneous Saccharification and Co-Fermentation (SSCF) configuration, and a first-generation ethanol production process. Specifically, the focus was on the fermentation of hemicellulose hydrolysate obtained from pre-treatment for ethanol production. In a study conducted by Moonsamy (2021), a technoeconomic analysis was performed on a comparable approach involving the utilisation of molasses obtained from the sugar mill. This molasses was combined with bagasse and trash materials (Moonsamy 2021). This study will consider a comparable approach, focusing exclusively on the utilisation of sugarcane bagasse derived from the sugar mill. The sugar mill will be briefly explained in section 2.4.1

2.4.1. Sugarcane processing

According to Dogbe, Mandegari, and Görgens (2018), sugarcane occupies a significant position within the realm of crops at a global level, as it contributes to over 80% of the overall global sugar production. The processing capacity of a typical sugar mill in South Africa is 300 tonnes/hr sugarcane, which yields an output of 38.4 tonnes/hr raw sugar (Mandegari *et al.* 2017). Table 2-1 lists the average chemical components of sugarcane (Ahmad *et al.* 2021). The lignocellulosic part of sugarcane, which makes up about 12.72 % of the weight, is made up of cellulose, hemicellulose, and lignin. Acids and potassium salts are examples of impurities

found in sugarcane. Potassium oxide is the major mineral found in sugarcane. According to Table 2-1, the soil component, which is picked up during harvesting rather than being a structural component of the sugarcane, makes up around 0.6% of the overall composition.

Table 2-1: Sugarcane composition (Ahmad *et al.* 2021)

Component	Composition (mass %)
Sucrose	13.3
Cellulose	4.77
Hemicellulose	4.53
Lignin	2.62
Reduced sugars	0.62
Minerals	0.2

The sugarcane crop from the field undergoes harvesting and is subsequently transported to the sugar mill, where it is carefully managed and prepared for processing. The production of raw sugar from sugarcane involves a series of sequential steps, namely extraction, clarification, evaporation, crystallization, centrifugation, and sugar drying. The description of these processes is presented below. Figure 2-1 illustrates the main by-products of each process (Dogbe, Mandegari and Görgens 2018).

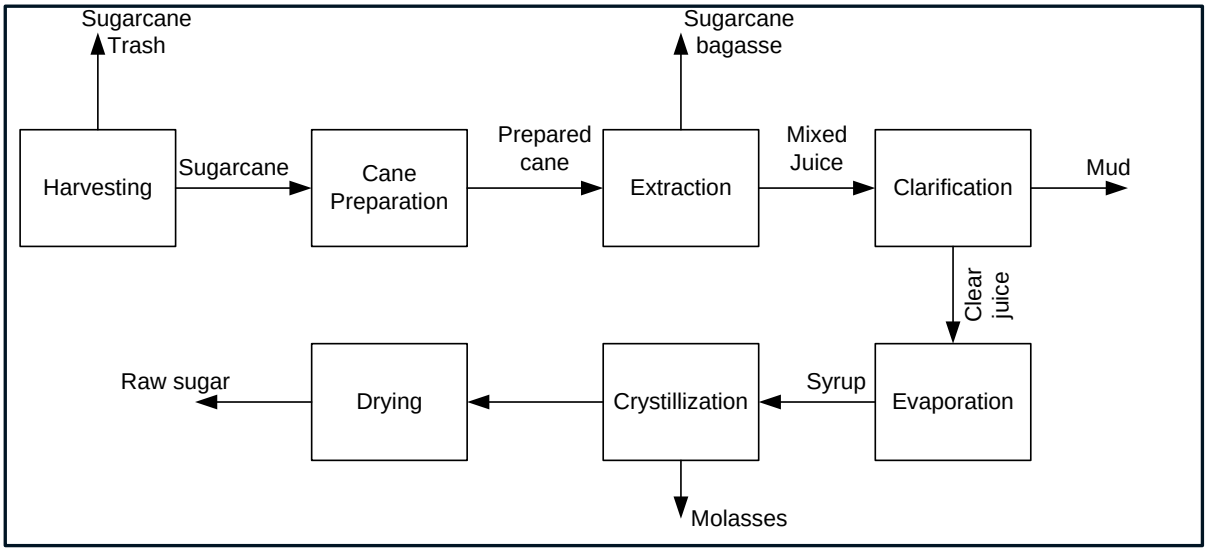

Figure 2-1:A typical process block diagram of the sugar mill (Dogbe, Mandegari, and Görgens 2018)

Harvesting

The primary methods employed for the harvesting of sugarcane include manual labour and mechanical means. The process of harvesting is typically carried out through manual means, utilising hand knives, such as cane knives, or hand axes. The field is first set on fire (cane burning) when harvested by hand. The fire quickly burns dry leaves, leaving water-rich stalks and roots. Harvesters can cut sugarcane above ground with knives. Mechanical harvesting uses a sugarcane chopper. Machines cut shorter stalks and remove leafy tops from cane rows. This method involves trashing, where sugarcane trash is produced. For the cane burning method, trash is burned; it does not come as a by-product. Depending on the method used, the sugarcane trash can be available or not available for use, especially since the more common harvesting method being used in South Africa is cane burning (Department of Agriculture 2014; Luca *et al.* 2018).

Cane preparation

Sugarcane is first prepared before being sent to extraction. Sugarcane is prepared using cane knives and a shredder. The purpose of the knife set is to reduce the bulk of the cane, cut it up, and feed shredder. The sugarcane is further broken up by the Shredder to expose the sucrose-containing components (SASA 2021).

Extraction

Extraction occurs through milling or diffusion, resulting in draft juice and sugarcane bagasse as a by-product. To enhance the removal of sucrose from sugarcane fibrous material, water is added. (O'Hara and Mundree 2016; Feng *et al.* 2018). Extraction is normally achieved by means of diffusion or milling. Diffusion requires more water but uses less energy than milling and is therefore the preferred method. The bagasse from the extraction process has higher moisture; therefore, it is further removed through dewatering mills to a targeted 50% moisture content (Wieck *et al.* 2019). Typically, 270 kg of sugarcane bagasse is obtained from processing one tonne of sugarcane; for 300 tonnes per hour of crushed sugarcane, 81 tonnes per hour of sugarcane bagasse is obtained (Wieck *et al.* 2019; Kabeyi and Olanrewaju 2023).

Clarification

Impurities are removed from the draft juice during the clarification stage. This process is achieved by elevating the temperature of the juice above its boiling point and flashing for air bubble removal, which may interfere with settling during clarification. The juice is dosed with lime to facilitate the occurrence of precipitation and for pH adjustment. The lime juice is further dosed with coagulant to aid settling. The mud settles down while clear juice overflows in the clarifier. In processes where diffusion is used for extraction, mud is recycled back to the extraction process. While some processes further remove juice from the mud, this results in the formation of the filter cake (Chand, Arora, and Sharma 2024).

Evaporation

In the sugar process, evaporation is used to concentrate clear juice by removing water from it. Before the process of evaporation takes place, the clear juice undergoes preheating at a temperature of 110°C. This preheating facilitates the occurrence of flashing as the juice is introduced into the first-effect evaporator. The latent heat generated during the process of evaporation in multiple-effect evaporators is effectively utilised for subsequent evaporations. The concentrated juice from the evaporation process is called syrup (Sanadi and Khot 2024).

Crystallization and centrifuging

The syrup from the evaporators is heated in vacuum pans to promote crystallisation, sugar crystals are added, and a hot mixture of molasses and crystals known as A-massecuite is formed. After cooling, the massecuite is filtered and washed to remove the sugar crystals from the molasses. The A-molasses is produced from the washings of A-massecuite. A-molasses is further used to produce B-massecuite, from which B-sugar and B-molasses are produced. B-molasses is used to produce C-massecuite, and from C-massecuite, C-sugar and C-molasses are produced. C-molasses is called the final molasses, which is a by-product in the sugar process and is normally sold. A-sugar is the only final raw sugar product. B- and C-sugars are recycled and used in the crystallisation process to form sugar crystals (Morales *et al.* 2024).

Drying

Sugar crystals exiting the centrifuges contain residual moisture and are therefore dried using hot air in rotary or fluidised-bed dryers to achieve the desired moisture content for storage and transport (Sharief, Mohamed, and Saad 2022).

Boilers

In the South African sugar industry, it is common for modern boilers to generate superheated steam at a pressure of 3100 KPa and a temperature of 400 ℃. The boilers are specifically engineered to combust bagasse, coal, or a combination of both fuels, and are equipped with a comprehensive heat recovery system (Parvez and Kumar 2022).

Historically, the fuel demands of most sugar factories were adequately satisfied by the abundance of bagasse, with certain factories even experiencing an excess of this resource. Nevertheless, as the utilisation of bagasse in various alternative applications expands, the functioning of back-end refineries and the transition towards cogeneration, a growing number of factories are facing a shortage of bagasse. Consequently, these factories resort to employing alternative fuel sources, such as coal. This has resulted in an increasing interest in energy efficiency, with particular emphasis on the crucial role played by boiler efficiency. The efficiency of a boiler is influenced by various factors, including the boiler's configuration and operation, as well as the type of fuel utilised. The boiler feed system in the sugar industry is depicted in Figure 2-2 (IllovoSugarSouthAfrica 2023).

The electricity cogeneration has been adopted by the sugar industries in South Africa. Illovo, an established sugar mill, effectively utilises renewable resources to generate electricity, utilising sugarcane bagasse as its primary source. This fibrous residue is derived from the extraction process of sugarcane juice, and Illovo's use of this resource enables them to supply 90% of their annual energy requirements from their installed electricity-generating capacity. Electricity plays a crucial role in the sugar manufacturing process, primarily serving to energize milling, refining, and packaging operations. Additionally, it is utilised for powering irrigation systems in agricultural estates, fulfilling other business needs, and supplying electricity to residential villages whenever feasible. Ubombo Sugar Limited, situated in the nation of Eswatini, possesses the capability to produce an excess amount of electricity to cater to the requirements of the national electricity grid. The annual electricity production of Ubombo amounts to an estimated 165-gigawatt hours (GWh), with around 60 GWh being supplied to the grid (IllovoSugarSouthAfrica 2023).

Figure 2-2: Boiler bagasse feed (Illovo Sugar South Africa 2023)

2.5. Sugarcane bagasse

Sugarcane bagasse is a lignocellulosic byproduct derived from the process of sugarcane milling, which shows promising potential as a viable feedstock for the production of biofuels. Bagasse from sugarcane is made up of cellulose, lignin, and hemicellulose, alongside ashes and extractives. Table 2-2 shows the average chemical compositions (Dry matter) of sugarcane bagasse (Mandegari *et al.* 2017). Bagasse leaving the dewatering mills has 50% moisture content (Dogbe, Mandegari, and Görgens 2018).

Table 2-2: Average chemical compositions (Dry matter) of sugarcane bagasse (Mandegari *et al.* 2017)

Component	Composition (mass %)
Cellulose	41.1
Hemicellulose	26.4
Lignin	21.7
Ashes	4
Extractive	6.8

Cellulose is a crystalline polymer that does not dissolve in water, consisting of glucose units, which can generate C6 sugars, namely glucose and fructose. Cellulose is composed of monosaccharide units, specifically glucose, which are connected through 1.4-glycosidic linkages (Chaudhary, Jain, and Jaiswar 2022).

Hemicellulose is a polymer primarily composed of xylan, which has an amorphous structure. This polymer possesses the ability to produce C5 sugars, such as xylose and arabinose. According to Narisetty *et al.* (2022), the xylan layer exhibits resistance to enzymatic degradation, thereby posing challenges in the production of xylose. Lignin is an aromatic-rich

polymer, which has the highest level of resistance. The lignocellulose is not hydrolysed by enzymes because the skeleton of the Sugarcane bagasse (SCB) binds cellulose and hemicellulose (Xu *et al.* 2019). Sugarcane bagasse (SCB) needs to be pre-treated to remove lignin or release cellulose molecules for saccharification and fermentation.

2.6. Biofuels produced from sugarcane bagasse

2.6.1. Bioethanol

Ethanol is currently the most favourable blend for substituting gasoline (Rao *et al.* 2020). The manufacturing of this substance is achieved by either chemical synthesis or biochemical synthesis, with biochemical production being responsible for around 90% of the overall production volume (Clomburg, Crumbley, and Gonzalez 2017). The biochemical conversion of sugarcane bagasse (SCB) to ethanol involves pretreatment, detoxification, saccharification, fermentation, and distillation. Theoretically, about 300 Litres of bioethanol can be produced from one tonne of sugarcane bagasse. This is equivalent to 2336.8 kilograms of bioethanol per tonne of sugarcane bagasse (Dias *et al.* 2009; Chandel, Da Silva and Singh 2013; Pan *et al.* 2022). The bioethanol production from sugarcane bagasse (SCB) is often seen to exceed 200 kilograms of bioethanol per tonne of sugarcane bagasse (Wang *et al.* 2019; Nakasu *et al.* 2021; Valladares-Diestra *et al.* 2021; Zheng *et al.* 2021).

Another method employed in second-generation bioethanol production involves the combination of gasification and syngas fermentation technologies (Pati, De, and Chowdhury 2023). The process utilises the thermochemical method to generate synthesis gas through the process of gasification. The produced syngas is then fermented anaerobically using mesophilic bacteria to produce ethanol and acetic acid (Sun *et al.* 2018).

2.6.2. Bio-syngas

Bio syngas is classified as a low-density fuel due to its gaseous state (Zou *et al.* 2022). Bio-syngas is generated by the gasification process of sugarcane bagasse in the presence of steam, oxygen, or air. The byproducts of the gasification process include hydrogen, methane, water, carbon dioxide, ash, and other hydrocarbons. Bio syngas is widely recognized as a significant gaseous biofuel within the field (Inayat *et al.* 2020; Awogbemi *et al.* 2021). Additionally, bio syngas is used for heat and power generation in Otto engines connected to electrical generators

(Mahapatra *et al.* 2021). Over the past ten years, bio syngas has drawn a lot of interest because of its many benefits, which include higher reactivity, less waste production when utilised, reduced oxidants requirements, reactor simplicity, and ease of control (Awogbemi *et al.* 2021).

2.6.3. Biogas

Anaerobic digestion (AD) is a highly promising biochemical process that transforms diverse organic wastes into biogas. Biogas, a prominent gaseous biofuel, mostly consists of methane (50-75%) and carbon dioxide (25-50%) (Zabed *et al.* 2020; Zamri *et al.* 2021). Biogas has the capability to fuel motors or produce heat. Syngas and methanol manufacturing can utilise it as a source of nourishment (Kulkarni *et al.* 2021). Scientists are investigating the simultaneous production of hydrogen and methane (Adarme *et al.* 2017; An *et al.* 2020) as well as ethanol and methane (Nosratpour, Karimi, and Sadeghi 2018; Lima *et al.* 2022). Implementing these solutions can enhance the energy recovery of SCB, but they also introduce greater process complexity and necessitate further commercial assessment (Pan *et al.* 2022).

2.6.4. Bio-oil

Bio-oil production from sugarcane bagasse is produced thermochemically via a fast pyrolysis process (Gautam and Chaurasia 2020). Bio-oils can be utilised as low-cost fuels alone or in combination with fossil fuels to improve combustion qualities such as octane number, cetane number, and so on. Additionally, bio-oils have been combined with diesel fuel as additives to lessen particulate matter and soot generation in diesel engines. It is produced along with other products; however, it is the major product of the process. SCB bio-oil contains 32.5 wt.% water, which interferes with ignition and causes an increase in the Ignition Delay Time due to a decrease in the rate of vaporisation of the droplet in a burner (Ordonez-Loza *et al.* 2021). Bio-oil is typically unstable, corrosive, and acidic (pH 2-3), which causes issues with storage, piping, and transportation (Gautam and Chaurasia 2020).

Bio-oil can also be produced using hydrothermal liquefaction (HTL), which can be upgraded to a transportation fuel. Bio-oil from HTL is also reported to be unstable, which makes it difficult to transport it over long distances to refineries for upgrading (Forero *et al.* 2022).

2.6.5. Biohydrogen

Biohydrogen is a low-cost biofuel that generates both water vapor and energy when burned (Ananthi *et al.* 2024b). It has a wide range of applications, from transportation to electricity generation (Sindhu *et al.* 2020). Biohydrogen, the most abundant element in the universe, is a convincing energy source for a clean Earth. Biohydrogen technologies, on the other hand, face significant practical challenges because of insufficient substrate conversion and a low biohydrogen generation rate (Ananthi *et al.* 2024b).

2.6.6. Biobutanol

Butanol is compatible with today's automobile engines. It has a high energy content as well as a low water solubility, making it a viable option for gasoline replacement (Sindhu *et al.* 2020). It can be used as a drop-in liquid biofuel for blending with gasoline (Tsai *et al.* 2020). Biobutanol can be utilised for transportation fuel without modification due to its better heating value and best energy density (Liu *et al.* 2022). However, biobutanol has been reported to have some drawbacks due to its low yield, slow rate of fermentation reaction, and expensive production costs(Tsai *et al.* 2020; Liu *et al.* 2022). SCB is reported to have a biobutanol yield of 0.16 g biobutanol/g glucose (Tsai *et al.* 2020).

2.6.7. Bio-methanol

Methanol is suitable for fuel cell-powered vehicles due to its complete degradation in the presence of steam into carbon dioxide and water. Methanol (15%) can be mixed with 85% gasoline to be utilised in the current existing vehicles (Sindhu *et al.* 2019). Bio-methanol can be thermochemically and biochemically made (Kasmuri *et al.* 2019; Kulkarni *et al.* 2021). Thermochemical technologies are uneconomical and still in development. The biochemical route uses methanotrophic bacteria or AD, but these processes are still being tested in the lab and lack sufficient data. It has been reported that biochemical methanol production yields are significantly lower than thermochemical ones (Kulkarni *et al.* 2021).

2.7. Sugarcane bagasse conversion technologies

To convert biomass into biofuels, three main technological categories are utilised: thermochemical conversions, physicochemical conversions, and biochemical conversions.

Anaerobic digestion and fermentation are the two biochemical processes that are frequently used to convert biomass into bioenergy. Gasification, liquefaction, pyrolysis, and direct combustion are the thermal techniques that are routinely used to convert biomass into biofuels. Transesterification and mechanical extraction separation are examples of physicochemical conversions (Issa *et al.* 2020). Figure 2-3 shows the overview of various biomass conversion technologies.

Worldwide, there is an abundance of sugarcane bagasse (SCB), a biomass derived from agricultural waste from sugarcane processing. Researchers have explored the use of biomass for various applications, including energy production and environmental sustainability, due to its renewable nature and its availability in many regions. The biomass might be converted to meet energy needs with the appropriate technology. The next sections discuss in detail the most popular techniques for processing sugarcane bagasse into biofuel.

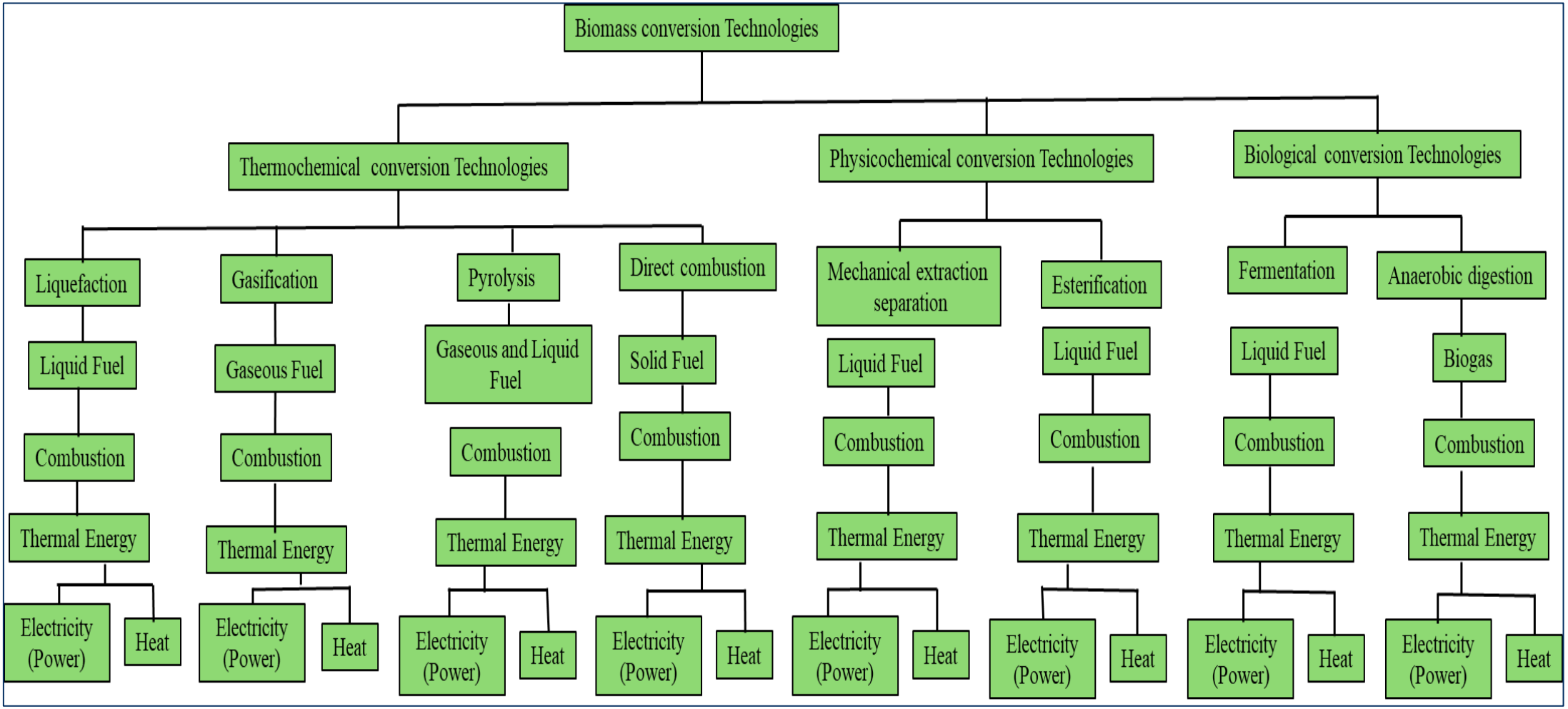

Figure 2-3: An overview of various biomass conversion technologies

2.7.1. Biochemical conversion

For the successful biochemical conversion process of SCB to biofuel, pre-treatment processes are important. The two biochemical processes of fermentation and anaerobic digestion are frequently employed to transform biomass into bioenergy. Good product selectivity and low processing temperatures are two advantages of biochemical techniques. Nevertheless, they frequently require a lot of pre-processing steps, extended processing times, low yields, and complex downstream processing, such as distillation, which consumes a lot of energy (Caroço 2019; Banerjee *et al.* 2023).

Biochemical conversion of biomass can yield a wide range of products, such as ethanol, hydrogen, biogas, acetone, butanol, organic acids, 2,3-butanediol, and isobutanol, when different microorganisms are used in the process (Daramola *et al.* 2021; Sadare *et al.* 2021). When considering biofuels as the focus of the current study, it has been possible to effectively produce a variety of biofuels utilising SCB as a feedstock, namely bio-ethanol, bio-methane, bio-hydrogen, and bio-butanol (Ajala *et al.* 2021). The biochemical conversion technologies will be discussed in detail after the detailed explanation of SCB pre-treatment methods.

2.7.1.1 Sugarcane bagasse preparation and Pre-treatment

Disrupting the crystalline structure of cellulose and dissolving the lignin structure is the main objective of biomass pre-treatment. This will facilitate the cellulose accessibility to enzymes during the biochemical conversion process; it is an essential tool for cellulose conversion processes (Reis *et al.* 2023). Pre-treatment is a significant cost component for biochemical conversion processes (Reis *et al.* 2023). It accounts for at least 20% of the total production costs (Wagle *et al.* 2022).

The pre-treatment method might be biochemical, chemical, or physical processes that are utilised separately, in combination, or in sequence (Galbe and Zacchi 2015; Silveira *et al.* 2015).

A broad range of chemical pre-treatment techniques has been investigated, with a thorough overview available in Kumar and Sharma (2017a). Figure 2-4 present a quick look at some recent advancements in pre-treatment methods that are frequently applied to the pre-treatment of lignocellulosic feedstocks.

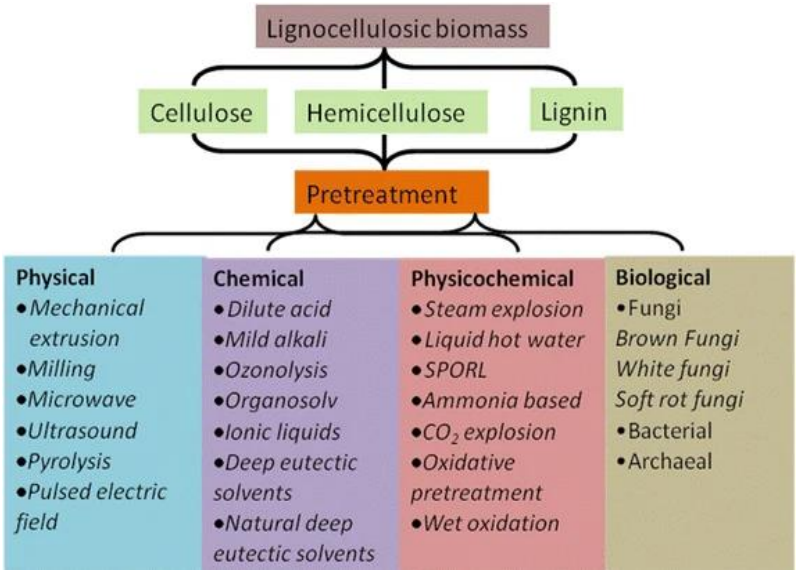

Figure 2-4 : An overview of various pre-treatment methods (Adepu Kiran and Shaishav 2017)

Various lignocellulosic materials have unique physicochemical properties, it is essential to choose the right pre-treatment processes for SCB (Gunes, Yaglikci, and Celiktas 2022). An efficient pretreatment ought to stimulate the production of fermentable sugars, reduce the loss or degradation of carbohydrates, limit the production of inhibitory byproducts, and be cost-effective, use little energy, and leave little or no residue (Poddar *et al.* 2022). Low sugar decomposition, low water or high solids, and minimal chemical use during the process are other factors that must be taken into consideration. Apart from that, pre-treatment should be performed carefully and with minimal operational risk (Bhutto *et al.* 2017).

Concentrated or diluted acid can be used for acid pre-treatments. Low temperatures between 30 and 60°C and acid concentrations between 40 and 80% can be used for concentrated acid hydrolysis. This method yields a large amount of sugar but requires a significant amount of acid. Reactors that are resistant to corrosion are necessary if a strong acid is utilised (Periyasamy *et al.* 2023)

Another chemical pre-treatment method that is becoming more popular for SCB pre-treatment is alkaline pre-treatment. It uses a variety of bases, including sodium hydroxide (NaOH)(de Carvalho, de Queiroz and Colodette 2016; Wunna *et al.* 2017; Ye *et al.* 2018; Yu *et al.* 2018), calcium hydroxide ($Ca(OH)_2$) (Rabelo, Filho and Costa 2009; Grimaldi *et al.* 2015), potassium hydroxide (KOH) (Paixão *et al.* 2016), sodium hydroxide (NaOH) in combination with

$Ca(OH)_2$ (lime) (Ahmadi *et al.* 2016). Despite the low cost of hydroxides, the drawback of this process is that huge volumes of biomass cannot be treated since it takes a lot of water to wash off the sodium (or calcium) salts that attach to the biomass. There is also a possibility that certain enzyme inhibitors will be produced as lignin depolymers (Chaturvedi and Verma 2013; Weng, Peng and Han 2021).

With its low capital costs, low energy needs, lack of chemical requirements, and extremely mild environmental conditions, biochemical pre-treatment is a promising approach. However, the primary disadvantages include the prolonged incubation period, low efficiency, significant loss of carbohydrates, the requirement for thorough growing condition monitoring, and restricted application space (Nahak *et al.* 2022).

One of the physical pre-treatment techniques is milling. Several milling processes, including vibratory milling, hammer milling, colloid milling, and two-roll milling, are used to increase the digestibility of lignocellulosic biomass. Milling is a less ideal alternative due to its inability to remove lignin, which restricts enzyme accessibility to the substrate (Sitotaw *et al.* 2021).

One of the most popular physicochemical methods for pre-treating lignocellulosic biomass is steam explosion pre-treatment (Agbor *et al.* 2011). In this process, biomass is subjected for a few seconds to minutes to high-pressure (0.7–4.8 MPa) saturated steam at a temperature higher than 160–260 °C, which causes hydrolysis and the release of hemicellulose. As the steam permeates the biomass, it widens the fibre walls, partially hydrolyses the biomass, and increases the accessibility of cellulose enzymes. The pressure is then reduced to atmospheric levels after that (Rabemanolontsoa and Saka 2016; Lynd *et al.* 2022).

Temperature, residence time, biomass size, and moisture content all have an impact on steam pre-treatment (Rabemanolontsoa and Saka 2016). Low temperature and longer residence time (190 °C for 10 min) perform better than high temperature and shorter residence time (270 °C for 1 min) due to low fermentation inhibitory product production in the earlier procedure (Sathendra *et al.* 2022).

It has been established that steam pre-treatment is effective in preparing agricultural wastes and hardwoods. The use of fewer chemicals, low energy needed, no recycling costs, and environmental friendliness are the advantages of steam pre-treatment. Nonetheless, a few catalysts, including H_2SO_4, CO_2, or SO_2, may significantly improve the steam explosion pre-

treatment effectiveness. However, there are many disadvantages to steam pre-treatment, such as the possibility of fermentation inhibitors developing at high temperatures, insufficient lignin-carbohydrate matrix digestion, and the requirement to wash the hydrolysate, which results in a 20% reduction in sugar yield (Baral *et al.* 2021).

A more recent technique for enhancing steam explosion pretreatment involves impregnating bagasse with sulphur dioxide (SO_2) instead of diluted sulphuric acid (H_2SO_4) to improve pretreatment efficiency. The amounts of xylose that could be made from xylan were higher when SO_2 was used to impregnate as opposed to when acid was used to catalyse the reaction (Yu *et al.* 2022). It makes sense that because sulphuric acid has a lower pH and less severe pre-treatment conditions follow, there should be fewer inhibitors produced by SO_2 impregnation than by H_2SO_4 catalysis. This theoretical consequence is supported by actual data from an experimental study by Wang, Wu, and Jönsson (2018).

In contrast to steam pre-treatment, liquid hot water (LHW) pre-treatment, often referred to as hot compressed water pre-treatment, uses water at high temperatures (170–230 °C) and pressures (up to 5 MPa). This releases the lignin and causes the hemicellulose to hydrolyse, increasing the accessibility of cellulose. Additionally, this stops the production of fermentation inhibitors at high temperatures (Agrawal *et al.* 2021). LHW requires low temperatures, produces few inhibitory compounds, and is cheap. However, downstream processing requires a substantial amount of energy due to the large volume of water involved (Beig *et al.* 2021).

One of the advantages of hydrothermal methods is that they do not require chemicals or expensive disposal charges (Awasthi *et al.* 2023). Additionally, because no acid is applied, there is no need for neutralisation or conditioning after pre-treatment, and because the particles break when boiled in water, there is less need for size reduction. Because of this, hydrothermal pre-treatment is desirable from an environmental and financial perspective (Konde *et al.* 2021).

2.7.1.2 Fermentation

Fermentation is the process by which microorganisms, including bacteria and fungi such as yeasts, convert plant-derived sugars into ethanol, butanol, and other by-products. Of all the biofuels, bioethanol has been studied the most. Recently, interest in bio-butanol has grown. Sugar crops have been utilised in the traditional process of producing ethanol; however, alternative resources, such as starchy crops or lignocellulosic biomass, can also be used. In the

presence of microorganisms, such as *Saccharomyces cerevisiae*, fermentation is often carried out at room temperature and atmospheric pressure (Abo *et al.* 2019). The reaction equations representing bioethanol fermentation are as follows:

Equation 1

$$C_{12}H_{22}O_{11} \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$$

Equation 2

$$C_6H_{12}O_6 \xrightarrow{\text{yeast catalyst}} C_2H_5OH + CO_2$$

Bioethanol is the primary biofuel product that is presently being investigated for biochemical lignocellulose processing. Anhydrous (99.5%) bioethanol can be added to gasoline and used as an oxygen enhancer or as a substitute for transportation fuel (Loyte *et al.* 2022; Greenfutureinnovations 2023). The four main steps in converting biomass to bioethanol are pre-treatment, hydrolysis, fermentation, and ethanol recovery (usually distillation) (Sabiha-Hanim and Halim 2018). Figure 2-5 below shows a general block flow diagram for a biochemical process for converting biomass to ethanol.

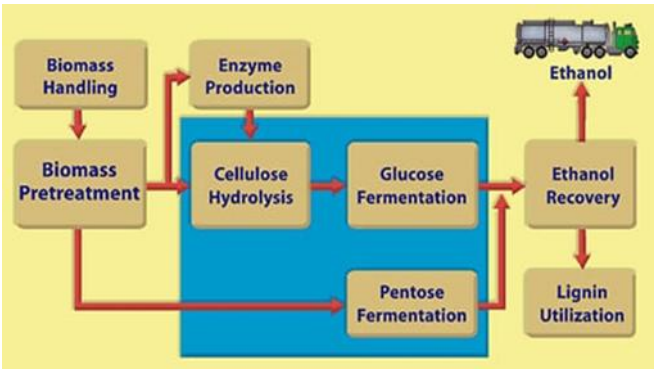

Figure 2-5: Generic biochemical processing of sugarcane bagasse to ethanol (Sabiha-Hanim and Halim 2018)

2.7.1.2.1 Hydrolysis and Fermentation

The hydrolysis process is used to transform feedstocks into fermentable sugars to produce bioethanol after pre-treatment. Acidic and enzymatic hydrolysis are the two most widely used methods (Kumar and Sharma 2017b). One major drawback of acid hydrolysis is the need to establish acid recovery and recycling procedures, which increase production costs.

Saccharification is best achieved via enzymatic hydrolysis because it provides simpler working conditions, lower energy costs, better selectivity, and higher yields than chemical methods (Kumar *et al.* 2020). Compared to acid hydrolysis of lignocellulose, enzymatic hydrolysis is more environmentally friendly, has lower energy consumption, and happens under milder reaction conditions (pH ≈ 5 and temperatures below 50 ºC). Additionally, it produces a high yield of glucose with fewer by-products (Bahlawan *et al.* 2022).

Enzymatic hydrolysis is a process that converts feedstocks into sugars that can be fermented. Enzymes, including endo β-1.4-glucanases, cellobiohydrolases, and β-glucosidases, are commonly used to break down cellulose. The source and concentration of the cellulase enzyme regulate its activity. Cellulose will be converted into reducing sugars under mild reaction conditions (pH: 4.8–5.0 and temperatures of 45–50 °C). Moreover, it prevents reactor corrosion, which can result in higher sugar yields. Enzymatic hydrolysis efficiency is affected by temperature, time, pH, enzyme loading, and substrate concentration, among other factors (Pino *et al.* 2018).

The three most common methods used in the production of bioethanol are: simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF), and separate hydrolysis and fermentation (SHF), which separates the hydrolysis of lignocellulosic material from the fermentation of ethanol; as a result, enzymes can be operated at high temperatures for optimal performance, while fermentation organisms can be run at low temperatures for optimal sugar consumption; SSF and SSCF have shorter overall processes because the enzymatic hydrolysis and fermentation processes take place concurrently to maintain low glucose concentrations; SSF separates glucose fermentation from pentoses, whereas SSCF ferments both glucose and pentoses (Sharma, Nair and Sarma 2021). Because the procedure may be done in the same tank, SSF and SSCF are preferable over SHF. Both methods have lower costs, better ethanol yields, and shorter processing times (Sharma *et al.* 2021).

Process integration techniques such as SSF and SSCF (simultaneous saccharification and co-fermentation) have been identified as ways to avoid inhibitory product formation (Bakhiet and Mahmoud 2015; Sharma, Nair, and Sarma 2021). Inhibiting chemicals can also be eliminated by detoxification. Activated charcoal addition, organic solvent extraction, ion exchange, ion exclusion, molecular sieves, over-liming, and steam stripping are some detoxification

technologies (Sharma *et al.* 2021). The most common detoxification method is over-liming with calcium hydroxide, but issues such as calcium salt precipitation on process equipment make this process undesirable (Sharma *et al.* 2021). Detoxification processes must be avoided wherever possible since they are costly and result in the loss of fermentable sugar (Chen *et al.* 2022b). Different types of microbes can handle different amounts of inhibition, so choosing a strong fermenting microbe could lessen the effect of compounds that stop fermentation. (Anwar, Gulfraz, and Irshad 2014).

Yeasts like *Saccharomyces cerevisiae* (*S. cerevisiae*) have been employed in alcohol production for thousands of years. This microorganism reduces distillation costs by providing a high ethanol yield, high productivity, and the ability to resist high ethanol concentrations (Kasavi, Finore, and Lama 2015). Yeasts are now utilised to produce fuel ethanol from renewable energy sources (Stambuk *et al.* 2019). *S. cerevisiae* is the most widely used yeast in industrial ethanol production because it tolerates a wide range of pH (da Silva Fernandes *et al.* 2022). This makes the process less vulnerable to infection. During sugar fermentation, yeasts face frequent difficulties such as temperature rise (35–45 °C) and ethanol concentration (above 20%) (Tofighi *et al.* 2014). As the temperature rises, the rate of growth and metabolism of yeast increases until it reaches the optimal value.

Microorganism development and viability can be inhibited by an increase in ethanol concentration during fermentation (Azhara *et al.* 2017). The inability of *S. cerevisiae* to grow in high-alcohol conditions results in ethanol production inhibition (de Souza Vandenberghe *et al.* 2020). Another issue in yeast-based bioethanol production is the capacity to ferment pentose carbohydrates. *S. cerevisiae* is the most widely employed yeast in the manufacture of bioethanol. It can, however, only ferment hexoses and not pentoses(Kumar, Singh, and Ghosh 2022). Only a few yeasts from the *genera Pichia*, *Candida*, *Schizosaccharomyces*, and *Pachysolen* can ferment pentoses to ethanol (Rech *et al.* 2019). Pentose fermentation issues can be handled by utilising a hybrid, genetically modified, or co-culture of two yeast strains. Hybrid yeast strains are utilised to ferment pentose and hexose carbohydrates to ethanol at the same time. The hybrid strain was created by fusing *S. cerevisiae* protoplasts with xylose-fermenting yeasts such as *P.tannophilus*, *C. shehatae,* and *P. stipitis* (Ruchala and Sibirny 2021).

A genetically modified *S. cerevisiae* strain and a co-culture of two strains have been created to generate high-yielding bioethanol from xylose. When compared to pure culture, co-culture produces more ethanol (Wang *et al.* 2022). Pentose-utilising yeasts such as *Pichia fermentans* and *Pichia stipitis* are co-cultured with *S. cerevisiae* to efficiently consume hexose and pentose sugars (Naseeruddin, Desai, and Venkateswar Rao 2021). The goal of co-culturing *S. cerevisiae* with other yeasts or microorganisms is to maximise ethanol output, minimize fermentation time, and lower process costs. This type of fermentation is called consolidated bioprocessing, where saccharification, hydrolysis, and fermentation are combined into one operating unit. It has advantages such as higher conversion compared to SHF (Naseeruddin, Desai, and Venkateswar Rao 2021), and it is less energy intensive and economical (Aui, Wang, and Mba-Wright 2021). However, it presents the challenge of the lack of suitable organisms that integrate all the features during the process, and it has the difficulty in process control (Naseeruddin, Desai, and Venkateswar Rao 2021). Following the fermentation process, the product acquired must go through a purification and distillation process to separate bioethanol from the fermentation broth to achieve the final pure bioethanol.

2.7.1.2.2 Ethanol Purification

The quantity of bioethanol generated during the fermentation process is mostly determined by the number of sugars produced during pre-treatment and the effectiveness of hydrolysis (Azman *et al.* 2015; Fockink, Maceno, and Ramos 2015; Tse, Wiens, and Reaney 2021). Following the fermentation process, the product must undergo purification and recovery. The fermentation product, known as beer, is refined in the ethanol recovery section, where carbon dioxide (CO_2), water, and lignin are separated from the beer to produce an ethanol product with a purity of 99.6 % and a recovery of 99.7 %. The specifications for ethanol purification are available from McAloon *et al.* (2000) for a second-generation ethanol plant using corn stover as a feedstock (McAloon *et al.* 2000). These specifications provide realistic estimates of ethanol purification from fermentation effluents, such as beer.

The CO_2 is removed in two flash drums, and any ethanol loss is recovered from the vapour in the scrubber. The liquid effluent from the scrubber is mixed with the liquid stillage from the flash drum and fed into the beer column. The beer column separates lignin and other heavy residues, yielding a 55 % ethanol distillate that is purified to 95 % in a rectifying column and

ultimately 99.6 % in the molecular sieves. The entire recovery section loses 0.3 % of its ethanol to the residues (Silva Ortiz, Maciel Filho, and Posada 2019).

2.7.1.2.3 Stillage utilisation

Stillage is the waste stream generated by distillation units. It is the whole fermentation liquid that remains after ethanol recovery; in the case of sugarcane bagasse, it is the lignin residue. Stillage can be seen as a resource rather than a waste, and many methods of exploiting it to create energy and co-products have been researched (Barta, Reczey, and Zacchi 2010; Uellendahl and Ahring 2010; Baral and Shah 2017). The solid lignin residue can be utilised to power a cogeneration plant that generates both steam and electricity. In comparison to other published stillage treatment methods, such as direct combustion of the solid fraction and evaporated liquid fraction (Aden and Foust 2009; Kazi *et al.* 2010; Gubicza *et al.* 2016), anaerobic digestion of stillage is less energy and capital-intensive, and more environmentally friendly. The use of biogas as a fuel derived from anaerobic digestion of stillage has been shown to enhance carbon use by eliminating the primary organic components (Uellendahl and Ahring 2010; Drosg *et al.* 2013; Tian *et al.* 2013). An integrated method for ethanol production in which biogas is created as a by-product is reported to optimise the energy input into the process (Cesaro and Belgiorno 2015). Anaerobic digestion simply eliminates organic carbon. Inorganic components of the stillage stream (such as Nitrogen, Phosphorus, Potassium, and metals, among others), as well as refractory compounds, might be utilised as fertilizer supplies for farmland in well-managed applications.

The influence of adding anaerobic waste stream digestion and nutrient recovery from digested effluent on overall mass and energy balance, as well as economic feasibility, was assessed (Wu 2018) ; the result showed that anaerobic digestion biogas could replace 68.3% of the fossil fuels utilised in the ethanol manufacturing process for steam generation. The revenue from the sale of phosphorus-rich fertilizer generated by the phosphate precipitation method lowered the ethanol production cost to 53.48 cents/L, down from 54.20 cents/L without waste utilisation. As a result, the stillage from the manufacturing of lignocellulosic ethanol should entirely be entirely used for energy and nutrient recovery (Wu 2018).

2.7.1.3 Anaerobic digestion

Anaerobic digestion is the process by which microorganisms break down biodegradable material in the absence of oxygen. Animal slurries, silage, food processing waste, and municipal solid wastes could all be used as biomass feedstock in anaerobic digestion. Microorganisms convert approximately 90% of the energy content of the feedstock into biogas, which contains approximately 50%-70% methane (Prabhu *et al.* 2021). Biogas produced can be used directly in spark-ignition gas engines and gas turbines, or it can be treated to remove CO_2 and improve its quality before being used to produce chemicals via dry reforming (Kabeyi and Olanrewaju 2022).

By choosing different microorganisms in the process of biochemical conversion, biomass can be transformed into a variety of products, including hydrogen, biogas, ethanol, acetone, butanol, organic acids (pyruvate, lactate, oxalic acid, levulinic acid, citric acid), 2.3-butanediol, isobutanol, xylitol, mannitol, and xanthan gum (Sadare *et al.* 2021).

Biogas is a gas generated by the anaerobic digestion of organic matter such as manure, sewage sludge, municipal solid waste, biodegradable waste, or any other biodegradable feedstock. Biogas is made up of methane and carbon dioxide. Anaerobic digestion (AD) or bio-methanation is a process in which organic matter is decomposed by microbiochemical activity in the absence of oxygen. Anaerobic digestion can be used to treat a variety of feedstocks, including animal manure, municipal solid waste, and agricultural waste(Mehta and Brezinsky 2023).

The AD process is subdivided into four stages: pre-treatment, digestion, gas upgrading, and digestate treatment. The degree of pre-treatment is determined by the kind of feedstock, and digestion occurs in the digester. There are many distinct types of digesters, each characterised by specific operating temperatures, mixing configurations, and design parameters. Depending on the solid composition, digestion might be dry or wet (Guvvala 2021). The efficiency of AD is influenced by several critical parameters; therefore, it is critical to provide suitable conditions for anaerobic microorganisms. Conditions such as oxygen deprivation, constant temperature, pH-value, nutrient supply, stirring intensity, and the presence and number of inhibitors all have a significant impact on the growth and activity of anaerobic microorganisms (e.g., ammonia). Because methane bacteria are anaerobes, the presence of oxygen in the digestion process must

be strictly avoided (El Asri 2022). Biogas from the digester includes pollutants that might harm boilers or engines; therefore, the biogas produced after the digestion step must be upgraded. For boilers and combined heat and power plants, hydrogen sulphide and water vapour must be removed. If the gas is to be utilised as a natural gas or motor fuel, carbon dioxide must be removed. The process has both economic and environmental benefits because effluents and emissions can be captured and reused (Wu *et al.* 2019a).

2.7.1.3.1 Anaerobic digestion process

The four phases of anaerobic digestion are acetogenesis, methanogenesis, hydrolysis, and acidogenesis. Specific microbes degrade complex compounds from organic matter into simple molecules at each stage, resulting in the final products of biogas and digestate. Proteins, polysaccharides, carbohydrates, and lipids degrade into simpler compounds such as sugars, amino acids, glycerol, and fatty acids during hydrolysis (Wu *et al.* 2019a). Following that, the hydrolysed molecules are primarily converted to acetate, volatile fatty acids, carbon dioxide, and hydrogen. This is known as the acidogenesis and acetogenesis stage. Finally, during the initial stage of methanogenesis, acetate, carbon dioxide, and hydrogen are converted to methane (Wu *et al.* 2019a). Biogas is a combustible gas that primarily consists of methane and carbon dioxide. Digestate is the decomposed substrate that results from biogas production (Teferra and Wubu 2018).

The anaerobic digestion process is based on interactions between the various bacteria capable of carrying out the four aforementioned steps. In single-stage batch reactors, all wastes are added simultaneously, and all four processes are permitted to proceed consecutively in the same reactor; the compost is then removed at the end of a set retention time or when biogas generation ceases (Meegoda *et al.* 2018). Figure 2-6 displays a simplified flow diagram of the four digestive phases.

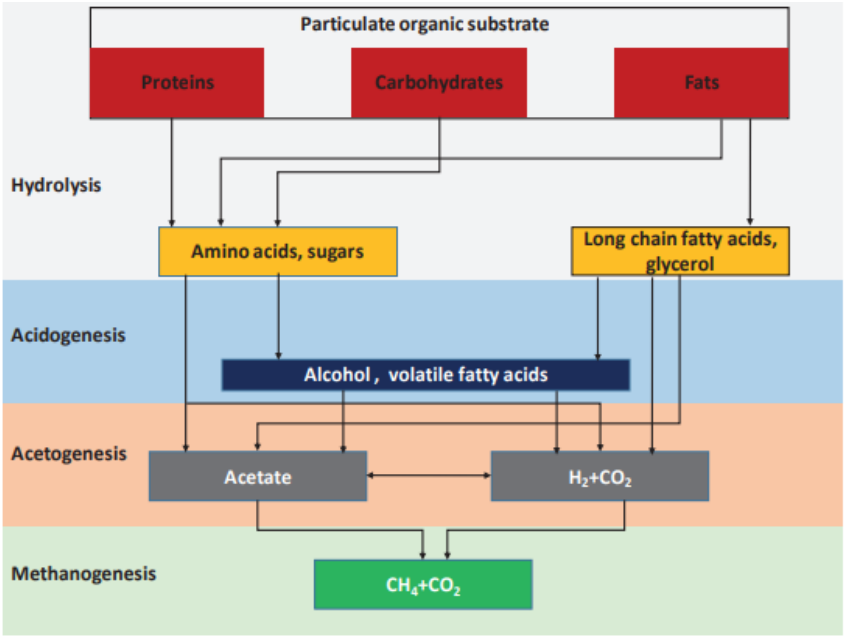

Figure 2-6: The simplified route diagram for anaerobic digestion (Azman 2016)

In general, anaerobic digestion is carried out in the form of a liquid with a total solid (TS) content of less than 15% (Ge, Xu, and Li 2016), which is referred to as wet (liquid state) anaerobic digestion. Wet anaerobic digestion is appropriate for wastes with low TS (high moisture content) (Riya *et al.* 2020). When handling wastes with high TS content, like lignocellulosic biomass, it needs a lot of water to keep the TS level in the reactor low, which increases the volume of the reactor and creates a lot of wastewater that needs to be treated (Ge, (Ge, Xu, and Li 2016). Furthermore, after wet anaerobic digestion, the digested slurry is subjected to a solid–liquid separation process for further processing (Logan and Visvanathan 2019). Dry (solid-state) anaerobic digestion, as opposed to wet anaerobic digestion, is defined as an operation with a TS content greater than 15% (Ge, Xu, and Li 2016).

An improved energy balance and a reduced need for fresh water are two benefits of dry anaerobic digestion over wet anaerobic digestion (Angelonidi and Smith 2015). Agricultural waste, such as lignocellulosic biomass, contains a high concentration of TS. Agricultural wastes can therefore be used for dry anaerobic digestion based on their TS content. After solid–liquid separation, the wet digestate solid fraction's total solid contents range from 23 to 30% (Nkoa 2014), which is either similar to or greater than the dry anaerobic digestate's TS content (TS content in the reactor) (Riya *et al.* 2018). Dry anaerobic digestion is therefore anticipated to minimize post-digestate treatment, including liquid fraction treatment and solid-liquid

separation, which can lower energy consumption as well as the costs associated with building and running the plants.

As a result, dry anaerobic digestion would be preferable to wet anaerobic digestion for an agricultural waste biorefinery. Although dry anaerobic digestion has several advantages, wet anaerobic digestion plants outperform dry anaerobic digestion plants in terms of energy balance and cost performance in practice (Angelonidi and Smith 2015), necessitating additional research on the effective operation of dry anaerobic digestion. The operating parameters for dry anaerobic digestion need to be properly chosen. High organic loading would decrease substrate breakdown and biogas production since dry digestive media often have insufficient mass transfer (Wang *et al.* 2023).

The AD process can occur at three different temperatures, which are classified as psychrophilic (below 25℃), mesophilic (25℃ – 45℃), and thermophilic (45℃– 70℃). The process temperature and the Hydraulic Retention Time (HRT) have a direct relationship. The minimum retention time for psychrophilic, mesophilic, and thermophilic conditions is 70-80 days,30-40 days, and 15-20 days, respectively (Admasu, Bogale, and Mekonnen 2022). When compared to conventional mesophilic digestion, thermophilic anaerobic digestion (45-70 ℃) has the potential to produce higher biomethane yields and a more organically stable, pathogen-free effluent (35-40 ℃) (Admasu, Bogale, and Mekonnen 2022). However, most commercial-scale anaerobic digesters have been operating at mesophilic temperatures up until now. In addition to the higher energy input, the thermophilic process has poor stability and reliability, which are the main reasons for its lack of adoption (Labatut, Angenent, and Scott 2014). It is unclear why thermophilic digestion is unstable. The primary hypotheses are a less diverse microbial community, propionate persistence, and increased intermediate toxicity at thermophilic temperatures (Li *et al.* 2024).

The pH of the AD substrate affects the growth of methanogenic microorganisms as well as the dissociation of some important compounds for the AD process (ammonia, sulphide, organic acids). Experience has shown that methane formation occurs within a narrow pH range, ranging from about 5.5 to 8.5, with an optimum pH range of 7.0-8.0 for most methanogens. Acidogenic microorganisms typically have a lower optimum pH value. The optimum pH range for mesophilic digestion is between 6.5 and 8.0, and the process is severely hampered if the pH falls below 6.0 or rises above 8.3 (Hitam and Jalil 2020). The pH is a determining factor in AD

because methane formation is inhibited at low pH levels. When the pH is too low, lime or sodium carbonate can be added to adjust it. This, however, may incur additional costs for the AD process (Sarker *et al.* 2019).

Both temperature and pH in the AD process have an effect on increasing the toxic compound formation. The toxicity of ammonia is affected by the operating temperature. The toxicity of ammonia increases with increasing temperature and can be alleviated by lowering the process temperature. However, when the temperature is reduced to 50°C or lower, the growth rate of thermophilic microorganisms drops dramatically, and there is a risk of microbial population washout due to a growth rate lower than the actual Hydraulic retention time (HRT) (Mukwevho, Maharajh, and Chirwa 2020). Toxic compound formation is affected by the pH and composition of the substrate. Substrates that comprise substantial quantities of lipids and carbohydrates are known to comprise ammonia, sulfides, and volatile fatty acids. These compounds have the potential to inhibit bacterial growth and methane production. At pH greater than 7, ammonia is toxic to the AD bacteria, while hydrogen sulfide and volatile fatty acids are toxic at pH less than 7 (Sapmaz *et al.* 2022).

Ammonia is an important compound that plays an important role in the AD process; however, excess ammonia concentration inside the digester, particularly free ammonia (the unionised form of ammonia), is thought to be the cause of process inhibition. The heavy metals are other harmful substances, but they are frequently found in low concentrations (Jiang *et al.* 2019).

In the AD process, pressure is the mixing power that affects gas recirculation, particularly in technologies without mixing equipment. A pressure increase during the AD process results in high carbon dioxide concentrations in the liquid phase. The solubility of carbon dioxide is higher than that of methane. Compared to methane, carbon dioxide is about 40 times more soluble. Consequently, raising the pressure may cause the substrate's CO_2 concentration to rise, which will promote the synthesis of methane. Additionally, lowering the pH value and the concentration of non-ionized ammonia are achieved by increasing the partial CO_2 pressure. Conversely, a drop in the partial pressure of CO_2 results in an increase in pH, which in turn reduces the amount of non-ionized hydrogen sulfide present (Kunz, Steinmetz, and do Amaral 2022).

The hydrogen partial pressure is another important parameter in the AD process. The hydrogen partial pressure should be low enough to provide a balanced environment for methanogenic

and acetogenic bacteria. Methanogenic bacteria use hydrogen to produce methane, so hydrogen availability is critical during the AD process. However, since acetogenic bacteria produce hydrogen, the partial pressure of hydrogen should be low enough to allow space for the hydrogen molecules produced by the acetogenic bacteria (Cazier *et al.* 2019).

For anaerobic digestion, there are two other operational and design parameters to consider. The organic loading rate (OLR) and the hydraulic retention time (HRT). The OLR specifies the amount of organic dry matter (DM) that can be fed into the digester per volume and time unit (Parajuli *et al.* 2022). Several factors influence the determination of the OLR, such as the type of digester, the substrate, and the temperature. The microorganisms must adapt to the rate of load; thus, it is important to determine the optimum frequency of loading the digester. At high altitude where the reactor operates at low pressure, the organic loading rate can be higher in comparison to reactors at sea level (101.3 KPa) due to their buffer capacity is being stronger (Corigliano *et al.* 2023).

The average duration of substrate storage in the reactor is known as HRT. This parameter is important for determining digester dimensions because it correlates digester volume with feedstock flow rate per unit time (Vögeli *et al.* 2014). The HRT should be long enough to ensure the presence of microorganisms in the substrate. HRT value decreases with increasing organic load. Therefore, it is not necessary for the number of microorganisms eliminated from the digestate to exceed the number of organisms that are reproduced. Higher methane yields and lower volatile solids are the outcomes of stable fermentations with extended retention periods (Lee *et al.* 2019). A long HRT is required in cold regions where the anaerobic digestion process is carried out at psychrophilic temperatures. According to research conducted in the Andean Plateau, producing biogas from animal manure requires 55-100 days of HRT. However, the rate of degradation varies depending on the characteristics of the feedstock (Tiwari *et al.* 2021).

2.7.1.3.2 Anaerobic hydrogen production

Anaerobes can produce hydrogen in anaerobic environments without sunlight by fermenting carbohydrate-rich substrates. The two stages of acidification and methane production in conventional anaerobic fermentation are well known. Through syntrophic interactions, specific microorganisms complete each stage. The first stage of acidogenesis produces hydrogen as an intermediate metabolite, and methanogens use it as an electron donor in the second stage. If

acidogens are left to produce hydrogen gas and other metabolites, and dark fermentation avoids methanogenesis and other hydrogen-consuming biochemical reactions, hydrogen can be harvested during acidogenesis (Lin *et al.* 2016).

Dark fermentation produces energy carriers like hydrogen gas, volatile fatty acids, and alcohols from substrates. Dark fermentation produces a gaseous product of primary hydrogen (70%) and CO_2, but may also contain CH_4, H_2S, ammonia, and water vapour. Biophotolysis produces only hydrogen. Purifying hydrogen is necessary for practical use (Gopalakrishnan, Khanna, and Das 2019; Ahmad *et al.* 2024). A second-stage process recovers energy residues in effluent as fatty acids and alcohols for energy production and water body protection (Kamran 2021). A general dark fermentation schematic diagram is depicted in Figure 2-7 (Kamran 2021).

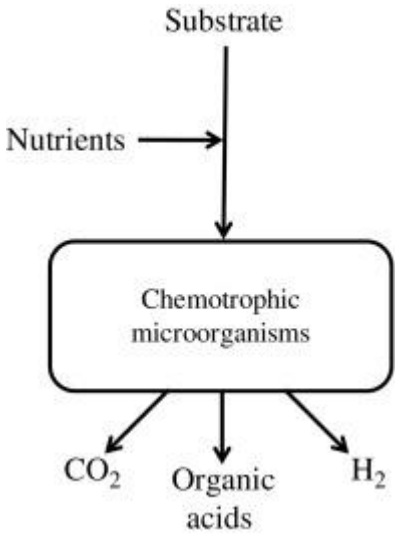

Figure 2-7: Simplified dark fermentation schematic diagram (Kamran 2021)

Dark-grown anaerobic bacteria on carbohydrate-rich substrates produce hydrogen. *Enterobacter, Bacillus, and Clostridium* produce hydrogen (Magrini *et al.* 2023). Hydrogen production by these bacteria depends on metabolic balance, pH, hydraulic retention time (HRT), and gas partial pressure. H_2 partial pressure is crucial to continuous H_2 synthesis. End products can inhibit hydrogen synthesis pathways due to H_2 concentrations. High H_2 concentrations reduce H_2 synthesis (Magrini *et al.* 2023). Dark fermentation biohydrogen production works best with sugars and carbohydrate-rich biomass. Dark fermentation is classified as mesophilic and thermophilic (Ananthi *et al.* 2024a).

It is highly recommended to maintain acidic and mesophilic conditions. Lowering pH levels to acidic values appears to be a promising approach to enhance hydrogen production by minimizing the transformation of hydrogen into methane. Dark fermentation (DF) naturally becomes acidic because of short-chain organic acids (SCOAs), allowing for the maintenance of an acidic pH without the need for pH-balancing chemicals, making the process more appealing and environmentally sustainable. Continuous fermentation significantly enhances productivity. The high substrate concentration, acidic pH, and short residence time are the most favourable conditions for hydrogen production. An anaerobic process involving hydrogen production in the first stage and methane production in the second stage could offer a promising alternative to existing methods (Moussa, Moussa, and Dionisi 2022).

2.7.1.3.3 Gas purification

The primary components of biogas are carbon dioxide and methane. Water vapor, nitrogen, oxygen, ammonia, and hydrogen sulfide are also present. These secondary elements and compounds typically account for no more than 10% of biogas content. They do not cause harm; however, when highly concentrated, they cause trouble or harm and reduce the heating value of biogas. The presence of oxygen can also lead to explosions. Hydrogen sulfide (H_2S) is both toxic to humans and harmful to pipelines and storage tanks. As a result, biogas treatment is required before this energy can be distributed to the public (Rafiee *et al.* 2021)

The gas produced from DF contains a mixture of hydrogen and CO_2; therefore, it requires downstream processing to purify and separate these gas components. Pure hydrogen can be used in fuel cells or combustion processes for generating electricity and heat, while the CO_2 can be sold to the chemical and beverage industry for reuse. Additionally, the VFAs generated in the liquid phase can be extracted and sold as high-value products for various uses in the chemical industry and to produce renewable energy biopolymers (Veluswamy *et al.* 2021).

When producing hydrogen with CO_2 capture, it is important to focus on the purity requirements for both CO_2 and hydrogen. The CO_2 purity requirements vary based on the mode of transportation (pipeline or ship transport) and the ultimate destination. When dealing with CO_2 captured from hydrogen or methane production, it is important to consider the impact of losing hydrogen or methane along with the CO_2. The presence of hydrogen or methane in CO_2 should be restricted due to their value as products, with the optimal limit determined by economic

factors. This is likely to increase the CO_2 purities to above 95% volume (Voldsund, Jordal, and Anantharaman 2016).

There are several methods for purifying gas, including high-pressure water scrubbing (HPWS), membranes, pressure swing, gas permeation, and chemical scrubbing. Two of the most common processes are high-pressure water scrubbing and chemical scrubbing (using amine solutions - MEA). The MEA scrubbing method uses aqueous monoethanolamine (MEA) to remove acidic gases. The general concentration of amine for acidic gas absorption is less than 30% by weight (Bragança *et al.* 2020). The amine process consists of two major steps: absorption and stripping (Wu *et al.* 2019a). High pressure water scrubbing, like MEA scrubbing, uses different gas solubility in water to upgrade gas: feed water to the bottom of the scrubber after biogas is pressurized to 10 bar, transfer CO_2-rich water to a flash column (3 bar) to minimize methane loss, and recirculate the CO_2-rich water through a desorption process (Paolini *et al.* 2021).

2.7.2. Thermochemical processing

Various thermochemical processes can be used to convert biomass into biofuels. The production of biofuels from synthesis gas derived from renewable resources is a significant step toward achieving zero greenhouse gas emissions required for sustainable development. As mentioned above, gasification, liquefaction, pyrolysis, and charcoal (direct combustion) are thermal techniques widely used to convert biomass into biofuels. The thermochemical conversion technologies are discussed in detail below.

2.7.2.1 Direct combustion

Direct combustion, also known as burning, is a high-temperature exothermic redox reaction that occurs when an oxidant, typically atmospheric oxygen, reacts with a fuel to generate oxidized, frequently gaseous products in a mixture known as smoke. Different types of solid material that can be burned to release energy, giving heat and light through combustion, are referred to as solid fuel (Salinas *et al.* 2020). Burning solid fuels produces more carbon, nitrate, and sulphate emissions. Solid fuels can contribute to poor air quality because they are made of organic components. Burning solid fuels produces more organic aerosol than liquefied petroleum gas and emits many volatile organic compounds, which can result in the creation of

secondary pollutants such as ground-level ozone and secondary organic aerosol, which can contribute to poor air quality (Xiong *et al.* 2020).

A boiler is a steam generator that generates steam by burning fuel. Water converted to steam is the most common fluid used in heat engines, which convert heat to work. In process applications, such as district heating by steam, heat from a steam generator can be used directly to meet the necessary process needs. The working fluid, combustion, and heat source are all isolated in steam generation by a wall made of heat-resistant material, such as steel tubes. Turbine-equipped steam generators are most frequently used to generate electricity. Boilers are commonly used in industrial-scale solid biomass combustion for heat and power generation. This technology allows for the use of a wide range of fuels, including those with high moisture and ash content. However, there are several issues with biomass boilers, such as pollutant emissions or ageing processes that can reduce boiler performance or cause damage, such as fouling, slagging, or corrosion (Kumar and Beohar 2022). Furthermore, direct combustion of bagasse in boilers has an efficiency of only 26%, and burning bagasse in boilers produces airborne fly ash, which is a major health hazard (Mavukwana *et al.* 2013; Gagliano *et al.* 2017).

The burning of sugarcane bagasse as a method of disposing of solid waste causes Kenyan sugarcane processing mills to waste enormous amounts of energy (Yuko 2005). Currently, sugarcane bagasse is used as a practical fuel for electricity generation in boilers, which powers the sugar factories. The method, however, is limited by the poor electrical efficiency of 20% compared to the gasification process with the efficiency of 80% (Gagliano *et al.* 2017).

2.7.2.2 Pyrolysis

Pyrolysis is the process whereby the solid biomass is heated to create gaseous compounds, liquid fuels, and solid char. It is a thermochemical method for converting biomass and organic materials into biofuels such as bio-oil, charcoal, and non-condensable gas. It is defined as the thermal breakdown of biomass in the absence of oxygen in a closed reactor. The distribution of pyrolysis products is influenced by process parameters as well as biomass composition. Lignocellulosic biomass pyrolysis starts with hemicellulose degradation at temperatures ranging from 197 to 275 ℃, cellulose follows at temperatures ranging from 273 to 347 ℃, and lignin is the last component to degrade at temperatures ranging from 277 to 497 ℃ (Bahú *et al.* 2022).

The kind of reactor, pyrolysis temperature, heating rate, biomass particle size, residence time, and sweeping gas flow rate (nitrogen) are the most essential characteristics. Pyrolysis product yield is influenced by operational factors, biomass qualities, and pyrolysis process type. Controlling and improving these variables is critical for ensuring proper product distribution (Zhang *et al.* 2007; Montgomery 2019). Pyrolysis has sparked the most interest in producing liquid fuel due to its advantages in storage, transport, and versatility in applications such as combustion engines, boilers, and turbines (Akhtar, Krepl, and Ivanova 2018).

The pyrolysis method includes the following four steps: Drying (100–200 °C), pyrolysis (200–500 °C), combustion, and reduction. Moisture is removed from the biomass through drying, and the biomass is then pyrolyzed at a higher temperature to break it down. The reaction pathway of the pyrolysis process is presented in Figure 2-8 below.

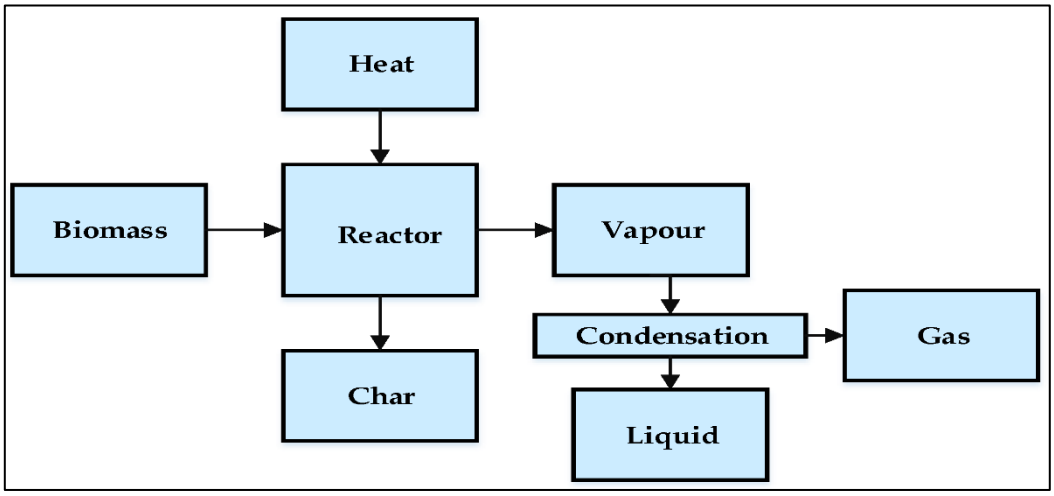

Figure 2-8: The general reaction pathway of the pyrolysis process (Zadeh *et al.* 2020)

The biomass is fed into the reactor after it has been dried and ground, and the pyrolysis process begins. Because the char produced in the reactor acts as a vapour cracking catalyst, char removal cyclones are used to separate the char from the reactor immediately after pyrolysis. Some small char particles, however, always pass through the cyclones and mix with the liquid product. To avoid continuous cracking of the organic molecules after solid (char) separation, the vapours and gases must be rapidly quenched. The vapours are typically quenched using pyrolysis liquid condensers, which cool the vapours directly with bio-oil or a hydrocarbon liquid (Meier 2019).

Pyrolysis is divided into three primary types based on parameters such as reaction temperature, heating rate, residence time, etc. In terms of heating rate, the process can be classified as slow, fast, and flash pyrolysis depending on the product preferences (Siwal *et al.* 2022). Table 2-3 shows how the temperature, residence time, heating rate, and products produced differ for each pyrolysis type. The pyrolysis types are further explained in the following subsections.

Table 2-3:Classification of pyrolysis type (Demirbas and Arin 2002)

Method	Temperature (°C)	Residence Time	Heating rate (°C/s)	Particle size (mm)	Major products
Slow pyrolysis	Med-high 400–500	Long 5–30 min	Low 10	5–50	Gases Char Bio-oil (Tar)
Fast pyrolysis	Med-high 400–500	Short 0.5–2 seconds	High 100	<1	Bio-oil (Thinner) Gases Char
Flash pyrolysis	High 700–1000	Very short <0.5 seconds	Very high >500	<0.2	Gases Bio-oil

Slow pyrolysis

Slow pyrolysis is a thermochemical technique used to decompose biomass; it favours the production of solid biochar and can take up to a few hours to complete (Zhang *et al.* 2007). The process operating conditions and products are presented in

Table **2-3**. Slow pyrolysis is the most widely used technology for producing biochar from biomass by tailoring the pyrolysis conditions and feedstock selection (Chen *et al.* 2022a; Das and Ghosh 2022). However, the vapours produced by biomass pyrolysis contain a high concentration of volatile organic compounds (VOCs), which are frequently overlooked and wasted as by-products in the biochar production process (Saraeian, Nolte, and Shanks 2019). These VOCs are frequently released into the environment, resulting in both pollution and energy waste. Even with the potential advantages, utilising condensable gases effectively in pyrolysis vapours remains a significant challenge because different gas components have different condensation points. Condensable pyrolysis vapours tend to form coke in the

equipment, which can reduce heat and mass transfer efficiency (Zhu *et al.* 2023). While some research employed catalytic reforming to transform high-grade bio-oil from condensable pyrolysis vapours, the procedures invariably consumed a significant amount of energy (Guo *et al.* 2020; Di Stasi *et al.* 2021; Zhang *et al.* 2021).

Fast pyrolysis

Fast pyrolysis is a technique for increasing the production of bio-oil (condensable vapours), and it works at a very high heating rate, reaching the process temperature in a matter of seconds. Fast pyrolysis uses feedstock with a maximum particle size of 2 mm. Fast pyrolysis at lower temperatures, higher heating rates, and small residence times favours liquid yield as the cracking of larger molecules to produce gaseous products is hindered. The process operating conditions and products are presented in Table 2-3. Liquid yield is also favoured by immediate and rapid quenching, which is often used to maximise the production of liquid products by condensing the vapours and gaseous molecules (Ibrahim 2020).

Although fast pyrolysis might be utilised to convert lignocellulosic biomass into liquid fuels on a large scale, its practical applicability is severely constrained by the uncontrollable quality of bio-oil derived from the complex and variable chemical compositions of lignocellulosic biomass. The heteroatoms in the biomass, in particular N, P, S, Cl, and alkali and alkaline earth metals, may have a significant impact on the quality of the bio-oil produced by the pyrolysis process. Furthermore, various pollutants such as NOx, SOx, and polycyclic aromatic hydrocarbons (PAHs) may be generated during the pyrolysis process, resulting in some environmental pollution difficulties (Pan *et al.* 2022).

Flash pyrolysis

Biomass flash pyrolysis is an advanced thermochemical conversion technology that converts low-grade biomass energy to high-grade biomass energy, with the main characteristics of a higher percentage of biological oil (brown liquid) in the terminal products. This brown liquid has a heating value between 15 and 19 MJ/kg (Ighalo *et al.* 2022).

Compared to other pyrolysis process types, flash pyrolysis is promising as products obtained can be used as feedstock for other re-refining processes. Furthermore, it is faster and can handle higher feedstock volumes at similar reactor volumes and process intricacies. Due to the

advantages of product yield, it is an important technology that should be explored for energy conversion of biomass and can also serve as a solid waste management technique (Ighalo *et al.* 2022).

Char Separation

Char is a solid intermediate residue formed in reactors during pyrolysis processes. Char separation must be quick and effective because it acts as a vapour cracking catalyst and contributes to the formation of polycyclic aromatic hydrocarbons (PAHs) in pyrolysis processes, especially at low temperatures(Cheng *et al.* 2018). Traditionally, chars are separated from reactors using the cyclone method, but this method has the limitation of passing fine particles through the cyclone, where they then collect in the liquid product, accelerating aging and causing instability issues. Although several alternative approaches, such as in-bed vapour filtration and rotary particle separation, have been used to overcome this limitation (Ha and Lee 2020).

These techniques are also challenging because of the complex interaction between the char and the pyrolytic liquid, which forms a gel-like phase that rapidly blocks the filter. Attempts have been made to solve this problem by modifying the liquid microstructure with solvents such as methanol or ethanol (Ha and Lee 2020). However, it causes solvent dilution of the liquid product and raises the overall cost of the process. As a result, research into appropriate mechanisms for char separation in pyrolysis processes is ongoing (Hoang *et al.* 2021b).

Liquid collection

Pyrolysis gaseous products primarily contain true vapour, aerosols, and non-condensable gases. These necessitate rapid cooling to minimize secondary reactions and condense the true vapours, whereas aerosols necessitate coalescence or agglomeration. However, due to severe fouling in the recuperators, high-temperature heat recovery is not desirable. Cooling with a simple heat exchanger, quenching in product oil or an immiscible hydrocarbon solvent, or the use of traditional aerosol capture devices such as demisters and electrostatic precipitators are the most commonly used methods for this purpose. Except for electrostatic precipitation, which is likely to be a preferred method for liquid separation at smaller scales up to pilot plant scale, none of these are particularly effective (Diao and Yang 2021).

In contrast, if the products of a pyrolysis process are liquids, high temperatures with short vapour residence times should be used (Ibrahim 2020). High residence times (1–1.5 hr) in fixed bed reactors, on the other hand, can produce high bio-oil and biochar yields, demonstrating how other operating conditions (e.g., reactor type and particle size) can influence yields as much as residence time and temperature. Non-condensable gas production via bio-oil degradation can occur at temperatures above 500 ℃ and with longer vapour residence times. If the gases are produced directly from the raw material, they are produced in short residence times in flash pyrolysis or gasification (Ighalo *et al.* 2022).

2.7.2.3 Gasification

Gasification is the oldest and most cost-effective method for the production of biofuels from biomass. Gasifying agents are used in the conversion of biomass into product gases such as carbon dioxide, carbon monoxide, methane, and biohydrogen at high pressures (1-33 bar) and temperatures (500-1400 °C) (Teixeira *et al.* 2022). Air and steam are the two most typical gasifying substances. The gasification process uses a range of feedstocks, including animal waste, municipal trash, wood chips, agricultural waste, and biomass from plantations (Akhlaghi and Najafpour-Darzi 2020). Gasification generates syngas, the ultimate products are methane (CH_4), carbon monoxide (CO), and hydrogen (H_2). Syngas produced by biomass gasification is appealing for energy applications. The composition of syngas varies depending on reactor operating conditions and can be tailored to specific applications. Power generation and fuel synthesis are the two most common syngas applications (Shukla and Kumar 2017).

Gasification is a thermochemical process that involves the interaction of biomass with oxygen, air, or steam to create a combination of gases, including CO_2, CO, CH_4, H_2, N_2, and hydrocarbons known as producer gas, syngas, or synthetic gas, the proportions of which vary. The primary goal of gasification is to maximise the production of gaseous products while minimizing the amount of unreacted char and condensable hydrocarbons. Table 2-4 summarizes the main chemical reactions occurring in biomass gasification (Kombe *et al.* 2022).

Table 2-4: Main chemical reactions occurring in a gasifier (Kombe *et al.* 2022)

Chemical reaction	Reaction name	Heat of Reaction (KJ/mol)
Heterogeneous reactions		
$C + 0.5O_2 \rightarrow CO$	Char partial combustion	-111
$C + CO_2 \leftrightarrow 2CO$	Boudouard reaction	172
$C + H_2O \leftrightarrow 2CO$	Water gas reaction	131
$C + 2H_2 \leftrightarrow CH_4$	Methanation	-75
Homogeneous Reactions		
$C + 0.5O_2 \rightarrow CO_2$	CO Partial combustion	-283
$H_2 + 0.5O_2 \rightarrow H_2O$	H_2 partial combustion	-242
$CO + H_2O \leftrightarrow CO_2 + H_2$	Water gas shift reaction	-41
$CH_4 + H_2O \rightarrow CO + 3H_2$	Steam-methane reforming	206
Hydrogen sulfide (H_2S) and ammonia (NH_3)formation reactions		
$H_2 + S \rightarrow H_2S$	H_2S Formation	
$0.5N_2 + 1.5H_2O \leftrightarrow NH_3$	NH_3 Formation	

There are three main types of gasifiers: fluidized bed, fixed bed, and entrained flow. The fluidized bed is split into three types: bubbling, dual, and circulating. Updraft, downdraft, and crossflow are types of fixed-bed gasifiers. They differ in the way biomass is fed into the gasifier, from the side or from the top, with or without gas flow, and in the higher or lower melting point of biochar and ash. The primary processes in gasification are the production of syngas, followed by its purification (Tezer *et al.* 2022). The primary steps in processing for biomass gasification are shown in Figure 2-9 below.

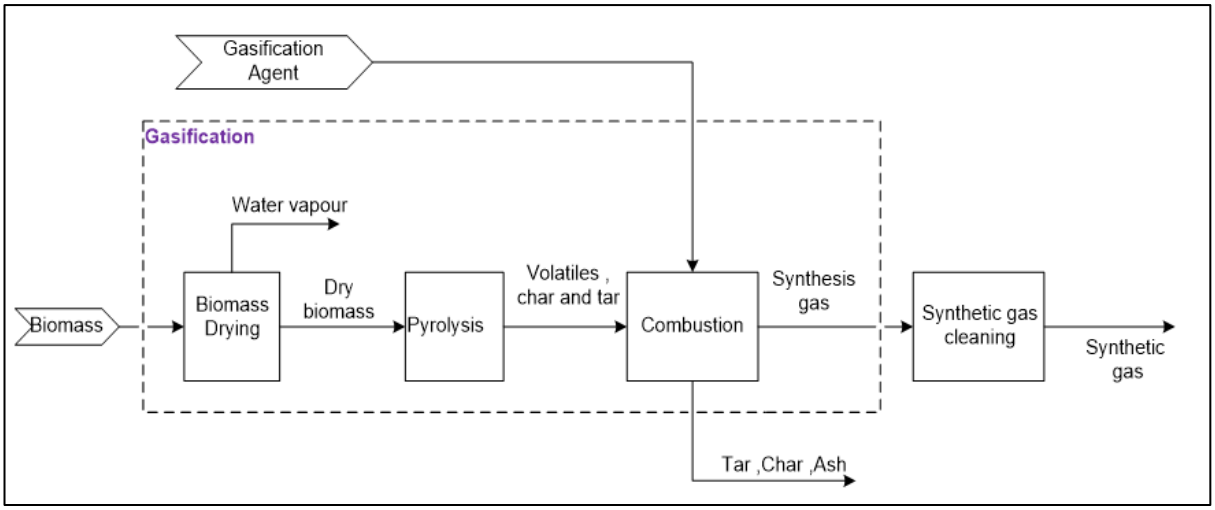

Figure 2-9: Biomass gasification basic process flow diagram

This process consists of a variety of physical and chemical processes, including rate-determining phases, and it occurs in the presence of a limited supply of O_2, such that partial oxidation can improve the overall efficiency. The position of the chemical processes is determined by the type of gasification technology used. The fixed bed gasifier is the most used type of gasifier. The fundamental chemical kinetics of each gasification technology are described, with an emphasis on the four main processes (drying, pyrolysis, oxidation, and reduction) that occur in the gasifier. The physical and chemical processes that characterize each zone, such as temperature, air moisture, heat losses, mass flow rate of air and gas, solid phases, feed rate, feed size, and moisture content, influence the magnitude of heat and mass flows (Mohammadi and Anukam 2022).

2.7.2.4 Hydrothermal Liquefaction

Hydrothermal liquefaction (HTL) is a low-temperature (250-350 ℃), high-pressure (5-20 MPa) process that takes place in the presence of a catalyst. HTL is particularly suitable for high-moisture feedstocks (Song *et al.* 2020). The technique yields a commercial liquid product. In the case of liquefaction, biomass macromolecule compounds are broken down into smaller molecules using an organic solvent or an aqueous media, with or without the use of a catalyst. As a result, the produced tiny molecules are unstable, reactive, and capable of repolymerising to form oily compounds with a wide range of molecular weight distribution. The micellar-like broken-down pieces created by hydrolysis are reduced to smaller compounds during the liquefaction process by dehydration, dehydrogenation, deoxygenation, and decarboxylation. Once created, these substances reorganize through condensation, cyclization, and polymerisation to create new substances. A solid charcoal residue is produced along with the thermal depolymerisation and degradation of biomass, cellulose, and hemicelluloses (Adeoye *et al.* 2023).

HTL produces bio-oil and other by-products such as char, water-soluble compounds (WS), and gases. Temperature, residence duration, heating rate, feedstock particle size, and solvent media type all have an impact on the HTL process, according to studies, with temperature, pressure, and solvent media being critical parameters (Nallasivam, Prashanth, and Vinu 2022). Figure 2-10 shows the effect of temperature on product distribution. Under 200℃, the solid product (char) dominates hydrothermal reactions at various temperatures. At temperatures exceeding 250℃, the production of liquid product (bio-oil) increases dramatically and reaches its peak

around 300℃. HTL is most active around 300℃, but the actual temperature varies depending on the feedstock (Nallasivam, Prashanth, and Vinu 2022). In the contemporary HTL process, various organic solvents (along with water) are employed as potential hydrogen donors for the reactions in order to reduce the severe carbon production. Solid catalysts, particularly alkaline catalysts (e.g., Na_2CO_3, $CaOH_2$, $BaOH_2$, and LaC_3, among others), are also used to speed reactions in HTL and increase bio-oil production (Zhang and Zhang 2019).

Hydrothermal liquefaction (HTL) is being extensively researched as a promising thermochemical conversion technique for bio-oil production, as the process is carried out under relatively mild conditions, resulting in reduced energy requirements.

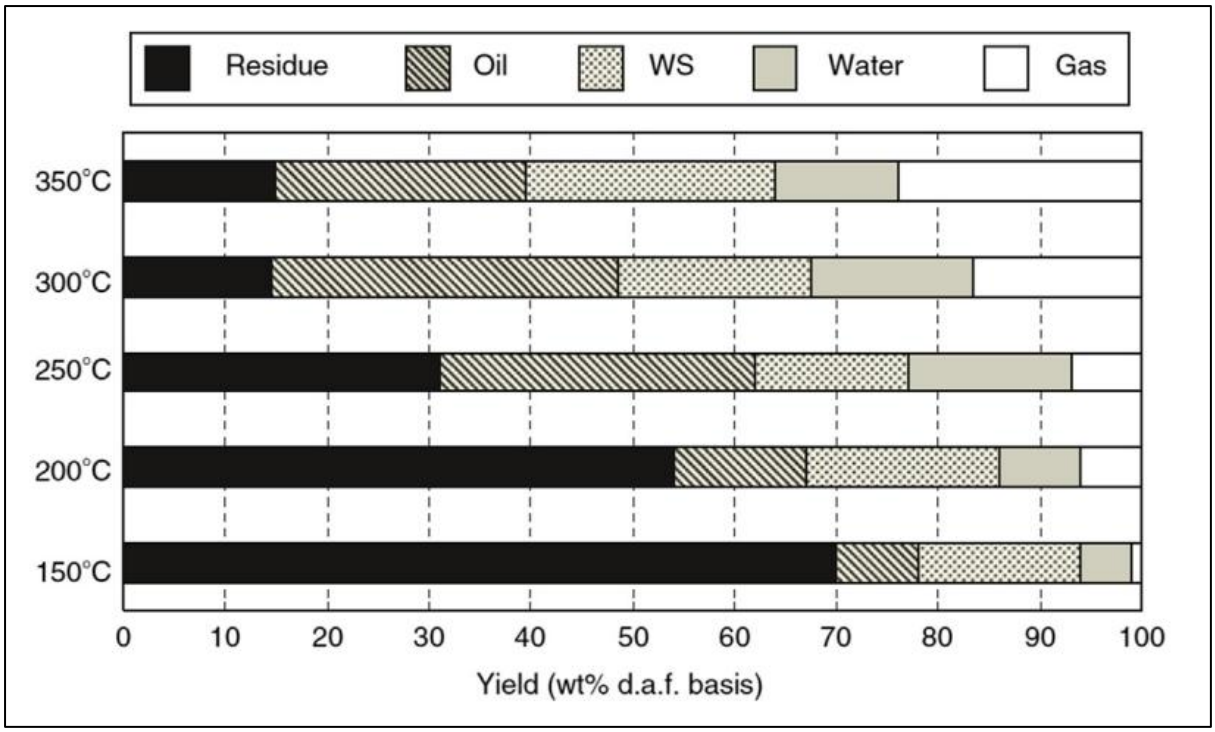

Figure 2-10: Temperature effect on Hydrothermal Liquefaction product distribution (Nallasivam, Prashanth, and Vinu 2022)

In addition, HTL feedstocks do not require energy-intensive drying, and the process produces relatively low levels of emissions, such as NO_x, making it environmentally advantageous. However, HTL technology is still largely at the research and development stage. Several challenges, including the optimisation of operating conditions (e.g., tuning critical solvent parameters), selection of appropriate feedstocks for higher yields, and management of the high viscosity of bio-oil products, must be addressed before HTL can be widely adopted for industrial bio-oil production (Zhang and Zhang 2019).

Following hydrothermal liquefaction, the reaction mixture separates into distinct phases, typically comprising a bio-oil phase, an aqueous phase containing dissolved organic compounds, a solid residue, and gaseous products. Separation of the bio-oil from the aqueous phase is commonly achieved through gravity settling or decantation due to density differences. In cases where stable emulsions are formed, centrifugation may be employed to enhance phase separation. Solvent extraction using organic solvents, such as dichloromethane or ethyl acetate, can also be applied to recover bio-oil from the aqueous phase, followed by solvent removal via evaporation. These separation steps are essential for maximising bio-oil recovery and ensuring accurate yield determination in HTL processes (Elliott *et al.* 2015).

2.8. Techno-economic assessment

The term techno-economic analysis (TEA) refers to a comprehensive methodology used to evaluate the economic viability and sustainability of emerging technologies. It provides a quantitative framework to evaluate the feasibility of implementing a technology in terms of both engineering and economic considerations, integrating both technical and economic aspects in the process. TEA is significant because of its capacity to provide information to decision-makers, investors, and policymakers regarding the economic repercussions that would result from the implementation of a specific technology. TEA use standard set of tools that includes extensive process simulations and financial models for assessing and comparing the technical and economic viability of different processing methods. Typically, software modelling is used to estimate capital costs, operating costs, and revenues based on technical and financial input parameters. Using visualization tools like tornado diagrams and sensitivity analysis graphs, one desired outcome is to summarize results in a concise and visually coherent manner (Barahmand and Eikeland 2022). TEA should be performed before attempting to transform a lab-scale project into a commercial plant. This enables one to acquire an understanding of the economic feasibility before commercialisation. Figure 2-1 presents the process flow of performing the TEA (Srinadh and Neelancherry 2023).

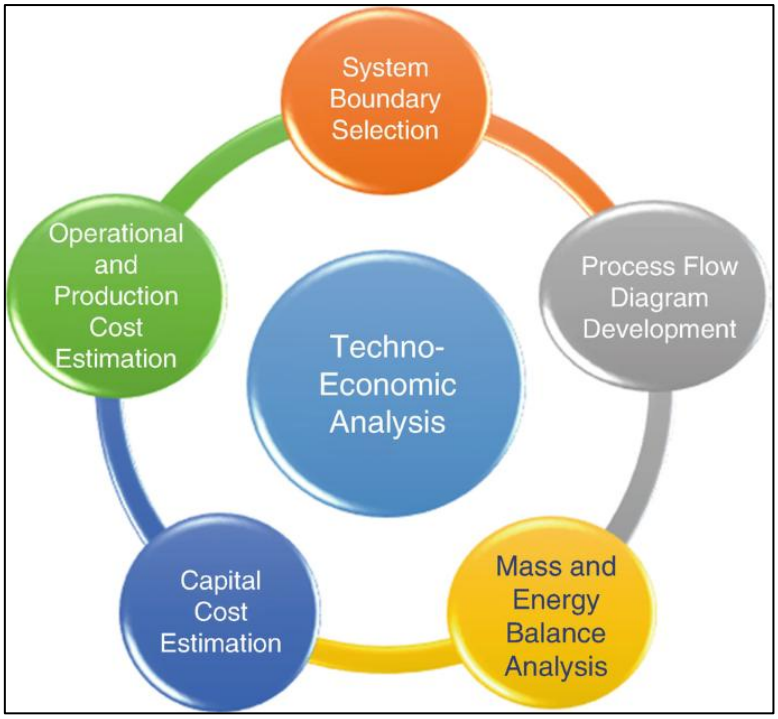

Figure 2-11:TEA process flow diagram (Srinadh and Neelancherry 2023)

Several studies have assessed the economic feasibility of producing biofuels from waste biomass. These studies aimed to compare various processing routes, feedstock types, plant sizes, co-production, feedstock blends, reactor configurations, and so on. Table 2-5 summarizes some of the TEA studies on biofuel production from sugarcane bagasse over the last five years.

The conducted techno-economic studies mainly cover the comparison of not more than three types of bioethanol processing routes. The current study aims to close this gap by evaluating all promising processing routes to convert sugarcane bagasse to biofuels. The current study further presents the environmental impacts of the process routes under investigation. Economic assessment entails the identification, quantification, and comparison of a proposal's expenses and advantages to determine its worth, either independently or in relation to other options. Economic assessment offers a systematic and organised method for evaluating a problem and potential solutions using well-established economic theory (Giacomella 2021). Economic evaluations can be utilised to forecast the anticipated expenses and advantages of a proposition and to furnish data to bolster the effective distribution of resources. Subsequently, a decision-maker can systematically evaluate various options, including the choice to maintain the current state, uniformly.

Economic assessment necessitates an estimation of capital costs, startup costs, fixed capital costs, working capital costs, operating expenditure costs, sales revenue, margin, and profit (Shields and Elvidge 2020). These are discussed in detail in the following subsections. Various techniques and parameters can be employed to conduct an economic evaluation. Commonly employed techniques and parameters for evaluating the overall quality of a proposal or comparing a group of alternatives include the payback period, rate of return on investment (ROI), net present value (NPV), internal rate of return, profitability index, and discounted cash flow analysis. These are normally called economic feasibility indicators. Economic assessments are just one type of analysis employed in the decision-making process. They should not be solely relied upon as they are rarely capable of providing the complete narrative. Non-quantified and non-monetized factors such as social and environmental impacts, as well as equity and distributional impacts, are crucial and should be considered in the decision-making process. Therefore, economic assessments should be used alongside other evaluation methods to ensure well-informed decision-making.

Table 2-5: TEA studies conducted on biofuels production from Sugarcane bagasse

Study area	Results	Reference
Techno-economic analysis of the thermal liquefaction of sugarcane bagasse in ethanol to produce liquid fuels.	Based on the plant life and a 30% corporate tax rate, the minimum selling price for fuel products was found to be $ 0.99/L. It was shown that semi-batch production was not as economically advantageous as continuous operation mode.	Ramirez, Brown, and Rainey (2018)
Comparative techno-economic analysis of biofuel production through gasification, thermal liquefaction, and pyrolysis of sugarcane bagasse.	Liquefaction generated the highest amount of product per kg feed, followed by pyrolysis and gasification. Based on net present values, the profitability was ranked as follows: pyrolysis > liquefaction > gasification. The plants were all sensitive to product price, thermochemical conversion ratio, and refining conversion ratio, thereby affecting profitability the most.	Ramirez and Rainey (2019)
Comparison of the techno-economic and life cycle analysis of a sugar production process using fuel oil or sugarcane bagasse for energy cogeneration of a sugar mill located in southern Mexico.	Sugarcane bagasse with a 2852 Te/d processing capacity over fuel oil proved to be more economical. First, energy production costs 5.5 USD/GJ vs. 14 USD/GJ for fuel oil, and second, the potential environmental impact index is 2528 vs. 20200 PEI/GJ.	Amezcua-Allieri *et al.* (2019)
Techno-economic assessment of bioenergy and biofuel production in an integrated sugarcane biorefinery.	Techno-economic analysis of first- and second-generation (1G2G) integrated sugarcane biorefinery producing ethanol and electricity was performed. This study shows that economic benefits depend on high final product yields and a set of industrial factors, proving that process simulation can identify industrial bottlenecks for future research.	Vasconcelos *et al.* (2020)

Exergy assessment and techno-economic optimization of bioethanol production routes.	Three scenarios were examined: sugarcane ethanol production-conventional pathway (1), sugarcane bagasse fermentation (2), and gasification (3). Exergy efficiency was highest in fermentation. It increased ethanol production by 22% and 45% over fermentation and gasification. The highest power generation configuration was gasification. The conventional pathway had the lowest CO_2 emissions (131.45 gCO_2/MJ products) and was the most sustainable configuration.	Ortiz, Marechal and de Oliveira Junior (2020)
Techno-economic assessment of one-stage furfural and cellulosic ethanol co-production from sugarcane bagasse and harvest residues feedstock mixture.	Assessed the production of furfural-only, ethanol-only, and integrated furfural-ethanol co-production under a variety of different operating conditions. The furfural-only biorefinery, was the most profitable, with an internal rate of return (IRR) of 12.92%. This was due to the fact that it was associated with lower total capital investments of $272 million and 51% bypass 51%. The integrated furfural and ethanol biorefinery was more profitable than the production of ethanol alone, with an IRR of 12.78% and 10.18%, respectively.	Ntimbani, Farzad, and Görgens (2021)
Techno-economic analysis and benchmarking of integrated first (1G) and second generation (2G) biorefinery scenarios annexed to a typical sugar mill for bioethanol production.	Compared to 2G ethanol production alone, which had a MESP of $1.44 per litre, 1G and 2G sugar integration were economically beneficial. Benchmarking 1G and 2G scenarios with industrial data yielded comparable investment costs for the developed 2G scenario and a 2G Brazilian facility. The best 1G2G scenario produced a MESP of $0.97 per litre by supplementing the whole pretreated slurry (2G) with molasses (1G) for Separate hydrolysis and co-fermentation sugar.	Moonsamy (2021)

Techno-economic evaluation of second-generation ethanol from sugarcane bagasse: Commercial versus on-site produced enzymes and use of the xylose liquor.	Biogas and ethanol production were assessed using two scenarios per biofuel. The first scenarios only utilise xylose for biofuel production, whereas the second scenarios are the production of biofuel from xylose liquor and the residuals of the onsite enzyme production process. These were assumed to be annexed to the sugar mill. The primary obstacle to the production of cellulase on site was found to be the requirement for an additional fungus strain for enzyme production.	Carpio *et al.* (2022)
Techno-economic feasibility and exergy analysis of bioethanol production from waste.	Bioethanol production from sugarcane bagasse (SCB) and brown algae was evaluated for 2000 Te/day of feed. The energy requirements were 625 kW and 180 kW for SCB and algae. The total capital cost per gallon of bioethanol was $17 and $12 for SCB and algae, respectively.	Joseph *et al.* (2023)

Non-quantified and non-monetized factors such as social and environmental impacts, as well as equity and distributional impacts, are crucial and should be considered in the decision-making process. As a result, some studies include both the techno-economic analysis and the life cycle assessment, where the life cycle assessment evaluates the environmental impacts. However, these types of studies are limited, particularly for sugarcane bagasse biorefineries. Among the nine studies tabulated in Table 2-5 only one study considered both techno-economic analysis and life cycle assessment (Amezcua-Allieri *et al.* 2019).

2.8.1. Capital expenditure

Capital expenditures, also known as CAPEX, refer to the financial resources that a company allocates for the purpose of acquiring, improving, and sustaining tangible assets such as real estate, facilities, infrastructure, technology, or machinery. CAPEX is frequently utilised by companies to pursue new projects or make investments. Capital expenditures on fixed assets encompass activities such as extending the useful life of a roof through repairs, acquiring equipment, or constructing a new factory (Brennan 2020).CAPEX is the total sum of start-up costs, working capital, and fixed capital investment. These are briefly discussed below.

Start-up costs

The expenses that are incurred by any new project during the process of its conceptualization are referred to as start-up costs (SUC). These costs include expenses that are required for budget planning, research work, advertising, borrowing expenses in the event that the project does not have its own capital, license and insurance charges, and other expenses. SUC are normally estimated as 10% of direct costs (Moonsamy 2021; Thoppil and Zein 2021).

Working capital

The ability to pay for day-to-day operations is crucial for every business, but it becomes even more important when sales or service revenues are slow, and the company needs money to cover basic expenses. This is where working capital comes in. Therefore, it can be described as the costs that are utilised to run the project during its initial phases, up until it can generate profit. The Working Capital is usually estimated as 15% of the total sum of the Inside Battery Limits and Outside Battery Limits plant costs (Towler and Sinnott 2021).

Fixed capital investment

Fixed capital investment is the amount of money that is required to get the plant ready for startup. This particular investment takes into account the costs of all of the equipment, construction, and ancillary buildings (Abdo *et al.* 2022). It is computed as the sum of Contingency Costs, Engineering Costs, Inside Battery Limits plant costs, and Off-Site Battery Limits Investment. Inside Battery Limits investment refers to the total cost of purchasing all major equipment and installations required to construct a new plant (Towler and Sinnott 2021).

In techno-economic assessments, it is common practice to use process flow diagrams, as well as mass and energy balances, to determine the installed costs, i.e., the inside battery limit (ISBL) plant cost. These balances are utilised to determine the dimensions and specifications of the process equipment that is being utilised. This makes it possible to estimate the cost of the equipment as well as the cost of installation. It is also a common practice to obtain the costs of equipment from the quotes provided by vendors. Using an appropriate scaling exponent, the costs of equipment of varying sizes are scaled based on the size of the equipment that was used for the initial price quote. After that, the cost of the equipment that has been installed is determined by applying installation factors, which are typically taken from reference books. These include the chemical engineering cost index (Chovau, Degrauwe, and Van der Bruggen 2013; Moonsamy 2021).

2.8.2. Operating expenses

Operating expenses (OPEX) refer to the expenditures related to the regular and ongoing operational functions of a business. These expenditures encompass various items such as rent, utilities, salaries, wages, office supplies, overhead expenses, property taxes, marketing expenditures, legal fees, and depreciation. Operating expenses (OPEX) are calculated by taking into account both the variable operating costs (VOC) and the fixed operating costs (FOC). The variable operating costs include expenditures associated with feedstock, chemicals, and make-up water. Fixed costs are expenses that remain constant regardless of the production volume. These may include costs for rent, labour, and other similar expenses. The sections below provide a concise explanation of the cost estimation (Jayathilaka 2020).

2.8.3. Total sales revenue

Total sales revenue, also known as gross sales, refers to the complete sum of sales generated during a specific time frame. The calculation of total sales revenue can be expressed in various

ways, although it is commonly derived by multiplying the total quantity of units sold by the price per unit.

2.8.4. Gross profit

Gross profit refers to the net profit generated by a business once all expenses associated with the production and sale of its products or services have been deducted. Gross profit can be determined by subtracting the cost of goods sold from the total sales. Gross profit is a metric that quantifies the effectiveness with which a business utilises its workforce and resources to produce goods or provide services to customers. It is a crucial metric for assessing the profitability and financial performance of a business. Gross profit provides insight into the expenses required to generate income. As the cost of goods sold rises, the gross profit decreases, resulting in a reduced amount of funds available to cover operating expenses. As the cost of goods sold decreases, there will be a corresponding increase in profit, resulting in a greater amount of funds available for business operations (ZohoBooks 2019) .

2.8.5. Discounted Cash Flow analysis (DCFA)

Discounted Cash flow analysis is an effective tool for planning and controlling financial activities. It is one of the most crucial instruments for financial analysis. The primary goal of DCFA is to determine the source and purpose of the funds. The cash flow statement shows if the business has made enough money to cover its expenses, buy new assets, and distribute dividends (Ivaniš, Filipović, and Ivaniš 2021; Hasibuan and Handriyani 2023).

2.8.6. Economic feasibility indicators

One of the most crucial elements of project design is economic feasibility. A project makes money all the way through to completion, but it also needs a sizable initial investment. Therefore, conducting financial and economic analysis is crucial; this is normally achieved by the determination of economic feasibility indicators (Singal *et al.* 2023). There are many economic feasibility indicators; however, for this study, only five of them will be considered. These include the payback period, rate of return on investment, net present value, profitability index, and internal rate of return (Thoppil and Zein 2021; Towler and Sinnott 2021). These economic feasibility indicators are briefly discussed below. The equations and formulas are further explained in Chapter 3 where appropriate.

Payback Period (PBP)

The time in years it takes to recover the cost of an investment is known as the payback period. In a nutshell, it's the amount of time it takes for an investment to break even. The payback period is crucial because the primary reason that individuals and businesses invest their money is to get paid back.

Rate of Return on Investment (ROI)

ROI is determined by dividing the profit generated from an investment by the initial investment cost. Return on investment (ROI) is the overall increase or decrease in the value of an investment during a specific time frame, stated as a percentage of the initial cost of the investment. When computing the rate of return, you are ascertaining the percentage increase from the commencement of the period to the conclusion.

Net Present Value (NPV)

Net present value (NPV) is a financial measure that aims to quantify the overall value of an investment opportunity. The concept underlying NPV involves forecasting all future cash inflows and outflows related to an investment, applying a discount to these future cash flows to account for their present value, and subsequently aggregating them.

Profitability Index (PI)

The profitability index (PI) is a metric that determines the desirability of a project or investment in terms of its profitability. It is determined by dividing the present value of anticipated future cash flows by the initial investment in the project. A PI value greater than 1.0 is considered a favourable investment, with higher values indicating more appealing projects. When facing limited funds and having to choose between different projects, it is advisable to only pursue the ones with the highest Profitability Index (PI).

Internal Rate of Return (IRR)

The internal rate of return (IRR) is the anticipated annual rate at which an investment is projected to increase. The Internal Rate of Return (IRR) is computed using the same principle as the Net Present Value (NPV), with the exception that it equates the NPV to zero.

2.9. Lifecycle Assessment

The Life Cycle Assessment (LCA) is a widely utilised analytical tool employed to evaluate the environmental implications associated with processes, services, and products. The analysis encompasses all aspects of the life cycle, including feedstock acquisition, manufacturing procedures, disposal methods, and production techniques. The evaluation of this assessment holds significant importance in identifying environmentally friendly processes and opportunities for process improvements(Munagala *et al.* 2021; Gheewala 2023).

LCA is transparent and reliable due to its standardization, which is governed by ISO 14040 and 14044. ISO 14044:2006 provides the guidelines for life cycle assessment. ISO 14040:2006, outlines Life cycle assessment principles and the framework. This standard contributes to the Sustainable Development Goals (SDGs)12 (responsible consumption and production) and 13 (Climate action). Four main LCA phases are described by these standards and include Goal and scope definition, Inventory analysis, Impact assessment, and results Interpretation. The steps are briefly discussed in the following subsections. Figure 2-12 illustrates the LCA methodology (Golsteijn 2020).

Several studies have assessed the environmental impacts of producing biofuels from waste biomass through life cycle assessment. Table 2-6 summarises some of the LCA studies on biofuel production from sugarcane bagasse over the last five years.

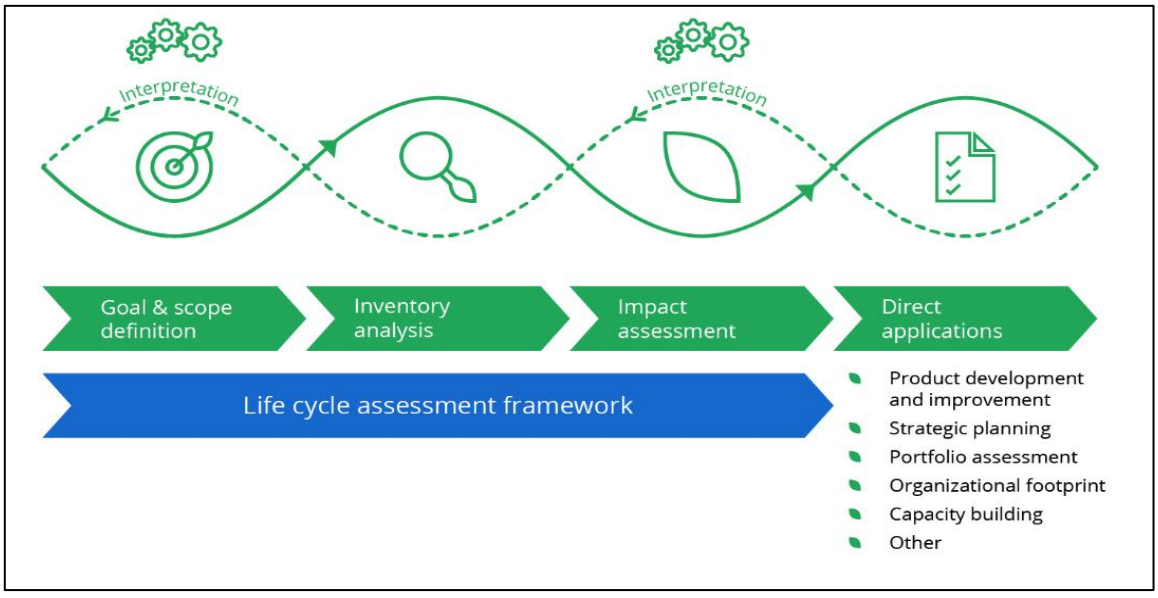

Figure 2-12: The iterative LCA methodology (Golsteijn 2020)

Table 2-6:Life Cycle Assessment (LCA) studies conducted on biofuels production from Sugarcane bagasse

Study area	Results	Reference
Energy cycle assessment of bioethanol production from sugarcane bagasse by life cycle approach using the fermentation conversion process.	Cradle to gate approach was followed, and three scenarios were assessed. Bioethanol production using fermentation, bagasse burning for electricity generation and co-production of bioethanol and electricity. Fermentation performed best environmentally, while the third scenario had the greatest negative effects on indicators of abiotic depletion and global warming potential. The third scenario was the best energy-wise.	Dibazar *et al.* (2023)
Life cycle assessment of bioethanol production from sugarcane bagasse using a gasification conversion Process.	A comprehensive assessment of the environmental effects of producing bioethanol from sugarcane bagasse was conducted in Mexico. This study employed a thorough cradle-to-grave approach to accurately measure the significant environmental pressures, as well as the cumulative energy requirements and water footprints. The global warming potential was 8.4 kg CO2-eq/L due to biofuel production and vehicle use. The biggest contributions were biofuel production with 55%-95% for Abiotic Depletion Potential, Marine Aquatic Ecotoxicity, Eutrophication, Ozone Layer Depletion, and Photochemical Oxidation Potential, and raw material extraction with 70%-100% for Land Competition, Human Toxicity, Fresh Water, and Terrestrial Ecotoxicity.	Santoyo-Castelazo *et al.* (2023)
A life-cycle assessment that compares various lignocellulosic ethanol production routes. This study examines the life-cycle assessment (LCA). The study mostly focused on evaluating different pre-	A cradle-to-gate system boundary and a functional unit of 1 MJ were used. Most categories were less affected by dilute acid pre-treatment with simultaneous saccharification and fermentation (SSCF). This combination had a global warming potential of 0.132 kg CO_2 eq. per MJ, with 85% of the contribution from steam generation. The impact can be	Murali and Shastri (2019)

treatment methods and different hydrolysis techniques.	reduced to 0.019 kg CO_2 eq. per MJ by using natural gas for steam generation. Due to ammonia production, ammonia fibre explosion pre-treatment had the greatest impact in many categories, emphasizing the importance of ammonia recycling. Dilute acid pre-treatment had less impact due to higher yields and lower biomass needs. Water footprint for ethanol ranged from 232 to 672 L/L, with agricultural water being the main contributor.	
An analysis of the environmental impact of producing bioethanol from sugarcane bagasse in Mexico, using a life cycle assessment approach.	A cradle-to-grave life cycle perspective was considered. The analysis considered a comprehensive life cycle perspective, from the production stage to the disposal stage. The carbon footprint amounted to 26,689 kilograms of carbon dioxide equivalent (kg CO_2eq), based on a specific functional unit of 1000 L of bioethanol. The bioethanol production accounted for the majority of the CO_2eq emissions, contributing 25.3%, while the use of bioethanol in vehicles accounted for 68.7%.	Zurita García (2021)
Life cycle assessment (LCA) of the energetic use of bagasse in the Iranian sugar industry.	An assessment was conducted to evaluate the environmental impacts of energy generation from bagasse and cane trash in Iran, using the cradle-to-gate life cycle impacts assessment methodology. The evaluation considered different methods of energy generation, including combustion, gasification, and anaerobic digestion (AD). When evaluating the potential for exporting surplus electricity to the grid and reducing greenhouse gas emissions, the combustion option demonstrates the most favourable results compared to gasification and AD. Utilising bagasse and cane trash for electricity production in the Iranian sugar industry will result in annual reductions of approximately 1.5, 0.7, and 0.9 million tonnes of CO_2eq emissions in the three examined scenarios (combustion, gasification, and AD).	Mohammadi *et al.* (2020)

2.9.1. Goal and scope definition

2.9.1.1 Goal

The goal describes the most important choices. This includes the reason for performing the LCA, its intended use, and the target audience. The South African Bill of Rights states that everyone has the right to a safe and healthy environment. Therefore, environmental guidelines are available to ensure that everyone complies. This has led to increased interest in LCA, with stakeholders aiming to prioritise processes that will have the least environmental impact. LCA can be used to identify opportunities to improve the environmental performance of products at various points in their life cycle. It can be used for marketing purposes, to make environmental claims, or create an environmental product declaration. LCA can be performed for decision-making during strategic planning, process design or redesign, or priority setting (Golsteijn 2020).

LCA studies for biofuels production are increasing and aim to investigate the potential benefits of bioproducts compared to conventional products. Various studies have different goals, but they all aim to maximise the use of a particular feedstock in biorefinery systems. This may include, among other things, production of a particular bio-based chemical from various feedstock types or evaluation of a particular biorefinery setup on a mixed input stream (Liu *et al.* 2018; Li *et al.* 2020; Al-Mawali *et al.* 2021; Hosseinzadeh-Bandbafha *et al.* 2022; Kovacs *et al.* 2022) . Nonetheless, one of the main objectives of LCA is that it should be sufficiently thorough to support decision-making (Bernstad Saraiva 2017).

2.9.1.2 Scope

Scope describes the functional unit, the definition of the product and its lifecycle, and the system boundary. The functional unit is the basis for comparison. It allows comparison of products based on similar functions. It serves as the standard against which all other assessment data are normalized. Therefore, the functional unit is the focal point of any life cycle assessment. In a comparative analysis, every compared product system functional unit must be the same. This is a prerequisite to guarantee equivalency between the product systems. Every product system's reference flow is established using the functional unit as a guide. A quantified quantity of the product(s), including product parts, required for a particular product system to

provide the performance specified by the functional unit is known as a reference flow. It could be the quantity of energy generated, the distance travelled, or the mass of feedstock processed (Hosseinzadeh-Bandbafha *et al.* 2022).

One of the most important steps in carrying out lifecycle assessments is setting system boundaries. To specify which processes are contained within the system boundaries, there are four primary options available: cradle to gate, gate to gate, cradle to grave, and gate to grave. Cradle-to-gate refers to the evaluation of a specific phase in the life cycle of a product, starting from the extraction of resources (cradle) and ending at the factory gate (i.e., before it is transported to the consumer). Cradle-to-gate assessments serve as the foundation for environmental product declarations (EPD) known as business-to-business EPD (Kavitha *et al.* 2020).

Cradle-to-grave assessment assesses the product's end-of-life disposal, which may involve a recycling process. Gate-to-gate is a Life Cycle Assessment (LCA) method that focuses solely on a single value-added process within the overall production chain. Gate-to-gate modules can be subsequently connected in their respective production chains to create a comprehensive cradle-to-gate assessment. It only considers the manufacturing process. Gate to grave LCA encompasses the transportation of completed products to customers, the utilisation of products by customers, the transportation of waste to disposal facilities, and the subsequent waste disposal procedure (Kokare, Oliveira, and Godina 2023).

2.9.2. Life Cycle Inventory (LCI) Analyses

The life cycle inventory analysis phase (LCI phase) is the second stage of LCA. It entails compiling a comprehensive inventory of input/output data related to the system under examination. This process involves gathering the necessary data to fulfil the objectives of the study. The input and output data for the life cycle assessment are primarily obtained from process mass and energy balances, while LCA software such as OpenLCA and SimaPro is used in conjunction with life cycle inventory (LCI) databases to provide background data for specific products and processes.

2.9.3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment phase (LCIA) is the third stage of the life cycle assessment (LCA) process. The objective of LCIA is to offer supplementary data to facilitate the evaluation of a product system's LCI outcomes, thereby enhancing comprehension of their environmental importance. LCIA is used to assess the possible effects of the processes/products under investigation. The evaluation process includes selecting impact categories for analysis, categorising LCI data, and computing potential effect indicators. Global warming, eutrophication, acidification, toxicity, and abiotic depletion are some types of impacts that are normally evaluated. Currently, different life cycle impact assessment (LCIA) methods are utilised for environmental impact assessment, including ReCiPe, TRACI, and the IPCC global warming potential method, which are implemented within LCA software such as SimaPro and GaBi (Golsteijn 2020).

2.9.4. Life cycle interpretation

Stage of life cycle assessment in which inventory analysis or impact assessment findings are compared to the goal and scope to draw conclusions and make recommendations. Life cycle interpretation is a methodical approach that involves identifying, quantifying, checking, and evaluating information that is derived from the outcomes of the life cycle inventory and/or the life cycle impact assessment. During the interpretation phase, a summary of the findings from the inventory analysis and impact assessment is included (Omolayo *et al.* 2021).

Chapter 3: Methodology

3.1. Introduction

This section describes the methodology utilised to achieve the objectives of the study. It provides an overview of the methodology that was utilised for the techno-economic assessment of biofuels production from sugarcane bagasse (SCB). Figure 3-1 presents the workflow for this study. The most appealing production processes for biofuel production from sugarcane bagasse were identified through literature research. To generate mass and energy balance data, Aspen Plus simulations were run for each of the selected process routes. Aspen Plus version 11 (V11) was utilised for the process simulations. Mass balance and energy requirements are presented in Appendix B. Mass balance and energy requirements were used as the basis for the economic assessment and lifecycle assessment. SimaPro software was utilised for lifecycle assessment.

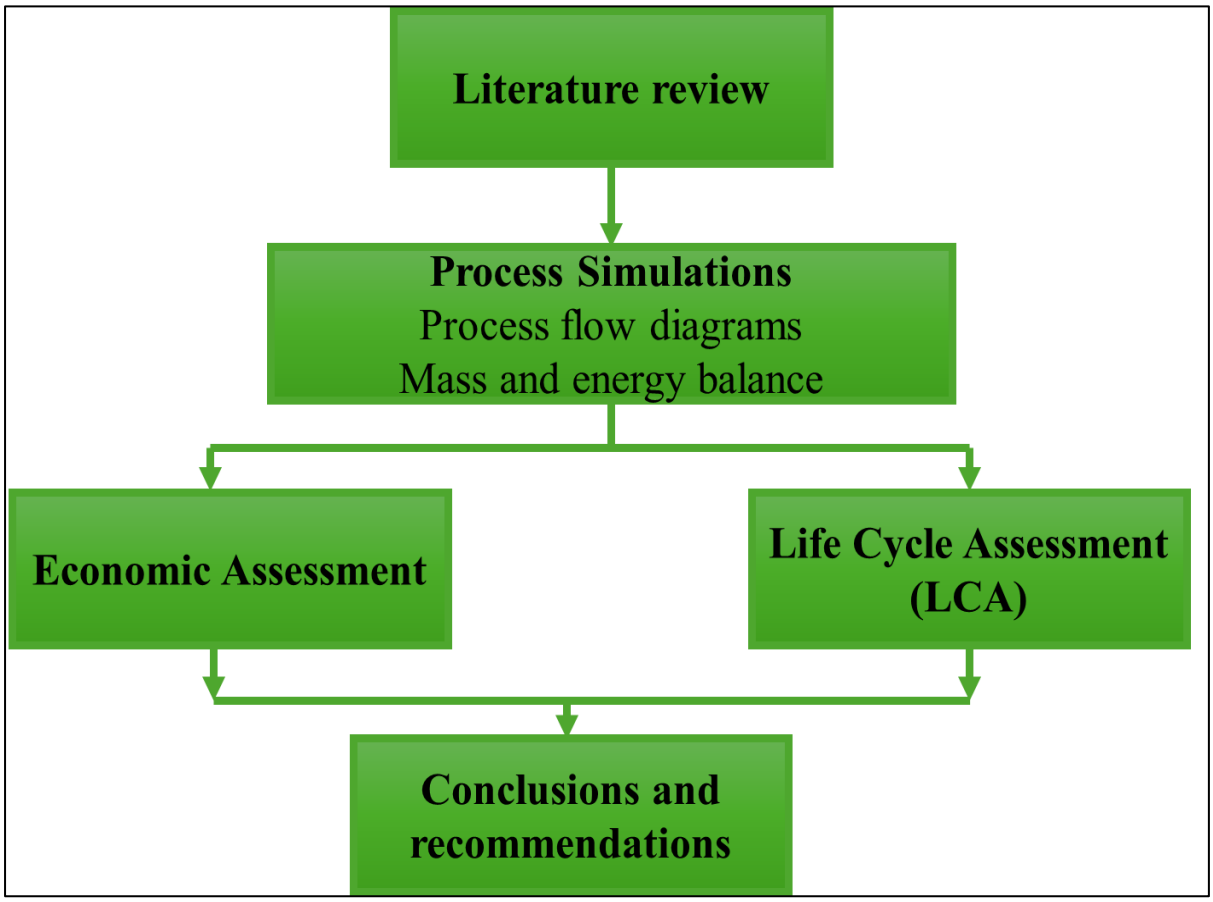

Figure 3-1: Workflow process flow diagram

This chapter consists of three sections, which aim to give a detailed methodology used in this study. Section 3.2 gives a detailed description of the process simulations. Five biomass-to-fuel conversion routes were simulated, namely, fermentation for bioethanol production; Anaerobic digestion for biogas production; Dark Fermentation for hydrogen production, gasification, and fast pyrolysis. The process flowsheets prepared from Aspen Plus software are presented in this section. Furthermore, the methodology utilised for the simulations is explained for each of the processing routes. Process simulations are crucial for the determination of mass and energy balances, which are used as the basis of economic and life cycle assessments.

Economic assessment is performed based on the mass and energy balance results from the Aspen Plus simulations. The methodology utilised for the economic assessment is presented in section 3.3. Economic indicators were calculated, including payback period (PBP), net positive value (NPV), internal rate of return (IRR), and profitability index (PI). This necessitated the calculation of operating expenses (OPEX) and capital expenditure (CAPEX). Furthermore, the discounted cash flow analysis (DCFA) was conducted. Economic assessment is crucial for determining the most economically feasible processing route.

To assess the environmental impacts of the processes, the lifecycle assessment was conducted using SimaPro software. The methodology utilised to conduct the life cycle assessment is explained in section 3.4. The results from Aspen Plus simulations were used as the basis for the life cycle assessment. SimaPro is crucial for determining the most environmentally friendly process route.

3.2. Process simulations

Five biomass-to-fuel conversion routes were simulated, namely fermentation for bioethanol production; anaerobic digestion for biogas production; dark fermentation for hydrogen production; gasification; and fast pyrolysis. These processes were simulated in Aspen Plus V11 to gather data for TEA and LCA of biofuel production from sugarcane bagasse. This study considered a typical South African sugar mill with a cane crushing capacity of 300 tonnes per hour. Typically, 270 kg of sugarcane bagasse is obtained from processing one tonne of sugarcane. Therefore, for 300 tonnes per hour of crushed sugarcane, 81 tonnes per hour of sugarcane bagasse is obtained (Miranda *et al.* 2021). An energy production system necessitates a bypass of 36% of the available lignocellulosic biomass, resulting in the remaining biomass

quantity of 51.84 tonnes per hour specifically allocated for biofuel production (Moonsamy 2021). The simulation methodology followed for each process is discussed in the following subsections. The biorefineries are designed to process 51840 kg/hr of sugarcane bagasse with 50% moisture content. Sample calculations are available in Appendix F for the estimation of biorefineries' feed rate and compositions.

3.2.1. Ethanol fermentation

Bio-ethanol production consists of pre-treatment, fermentation, and purification. Sugarcane bagasse (SCB) is pre-treated using steam explosion. The pre-treated slurry is fed into the fermentation reactor, where the sugars are converted to the fermentation broth. The fermentation broth then undergoes purification and separation to produce 99.9% pure ethanol. Pre-treatment, enzyme production, fermentation, and purification were simulated separately.

MIXCINC was specified as the global stream class. This stream class has three sub-streams: MIXED, CISOLID, and NC. This option is recommended when simulating both conventional components (MIXED), nonconventional solids such as carbon (CISOLID), and nonconventional feed such as biomass and ash (NC). For nonconventional components, only the enthalpy and density of biomass and ash were estimated during the simulation using the HCOALGEN and DCOALIGT models, respectively.

Sugarcane bagasse components were used to define it on the Aspen Plus software. Sugarcane bagasse components are hemicellulose, cellulose, and lignin. Lignin was specified as the non-conventional solid, whereas hemicellulose and cellulose were defined using their monomers $C_5H_8O_4$ and $C_6H_{10}O_5$, respectively. The chosen property method for simulation of the bioethanol fermentation process was the NRTL model that uses the Redlich-Kwong equation of state and is used for aqueous and mixed solvent applications. This property method has been used by various researchers previously (Leibbrandt 2010; Petersen 2012; Mandegari, Farzad and Görgens 2017).

Pre-treatment

The feedstock, sugarcane bagasse, is treated by steam explosion, impregnated with a sulphur dioxide catalyst for all the process scenarios (Petersen 2012; Mandegari, Farzad, and Görgens 2017; Moonsamy 2021). Sugarcane bagasse is first preheated to about 100°C using low-

pressure steam in a pre-steamer. Sulphur dioxide is prepared onsite using solid sulphur and oxygen from air. Bagasse is then impregnated with 2% SO_2 (w/w, amount based on SCB water content) for 30 minutes at room temperature (Carrasco *et al.* 2010). The sulphur impregnated sugarcane bagasse is then fed to the pre-treatment reactor, where bagasse is hydrolysed by means of steam explosion at 190 ℃ (Petersen 2012). The reactor is directly injected with 130 ℃ saturated steam. The reactions and conversion in the hydrolysis reactor are as presented in Table 3-1.

Table 3-1: Chemical reactions taking place in hydrolysis reactor and their conversions

Reaction	Conversion (%)	Reference
$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$ Cellulose + water → glucose	74.47	(Moonsamy 2021)
$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$ Hemicellulose + water → xylose	96.8	(Wu *et al.* 2019b)

The resulting pre-treated slurry (hydrolysate) is flashed, cooled, and fed to the fermentation reactor, whereas 10% of it is used to manufacture the enzyme in the seed reactor. The heat produced by vapour in the pre-treatment reactor is recovered and reused for preheating the fermentation broth before ethanol recovery. Figure 3-2 presents the flow sheet for SCB pre-treatment.

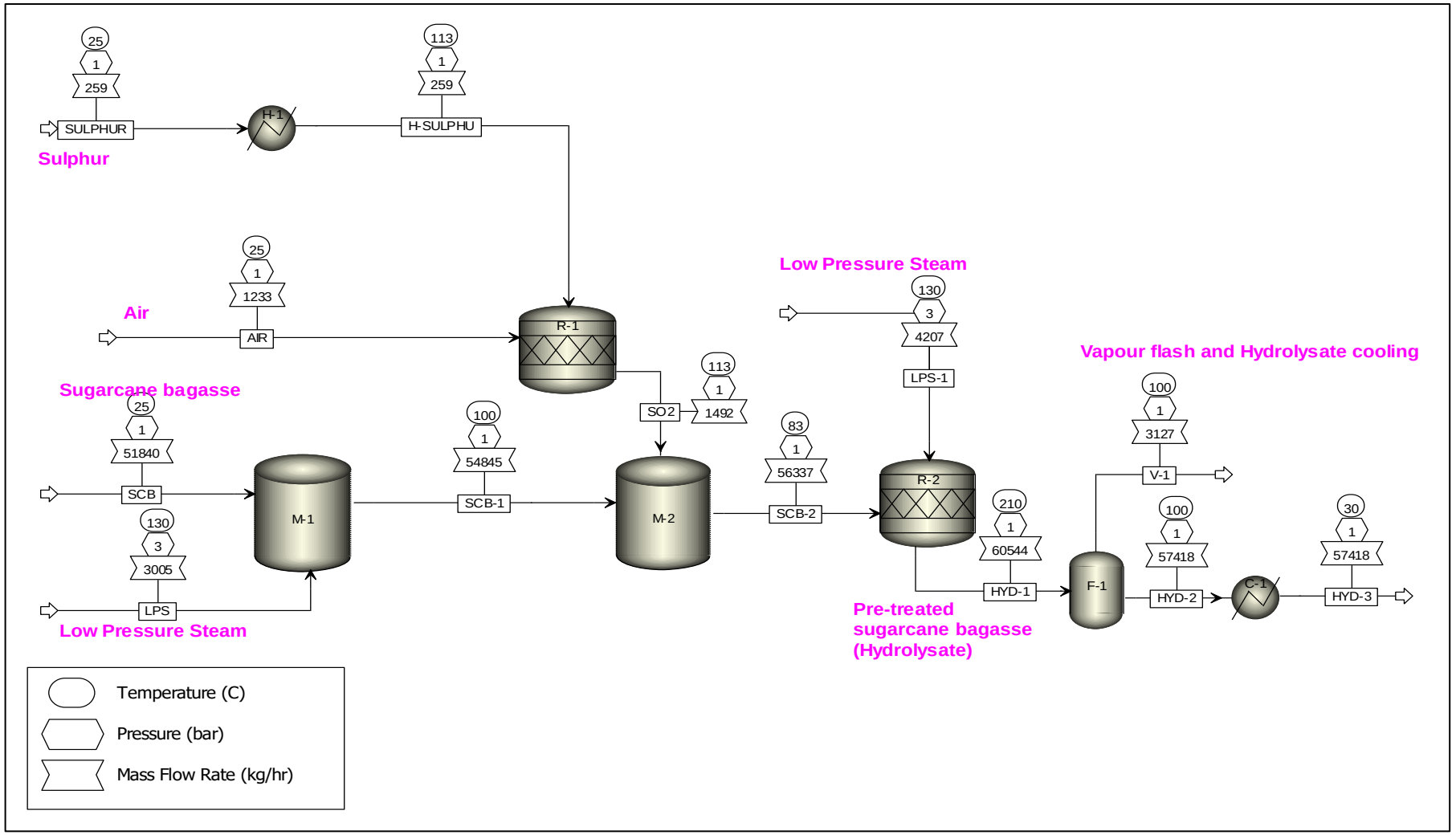

Figure 3-2: Aspen Plus flowsheet of sugarcane bagasse pre-treatment

3.2.1.1 Enzyme production

Fermentation is facilitated through the simultaneous saccharification and fermentation (SSF) technique, wherein the cellulase enzyme required for enzymatic hydrolysis is generated on site. This process involves utilising 10% of the pretreated slurry, along with necessary nutrients (Mandegari, Farzad and Görgens 2017). Diammonium phosphate (DAP), ammonia, microorganisms, and a fraction of the hydrolysate are combined before being added to the seed reactor, which operates 30 ℃ and 1 atmosphere for enzyme production (Humbird *et al.* 2011). Oxygen is also added to the reactor. The microorganism adopted in this study is *Saccharomyces cerevisiae*, normally shortened to *S. cerevisiae*. Small amounts of oxygen are needed by S. cerevisiae cells to synthesize sterols and fatty acids during the synthesis of bioethanol (Sanchez and Cardona 2008). Ammonia is fed into the seed reactor for conditioning purposes (Moonsamy 2021). Figure 3-3 presents the flow sheet for enzyme production.

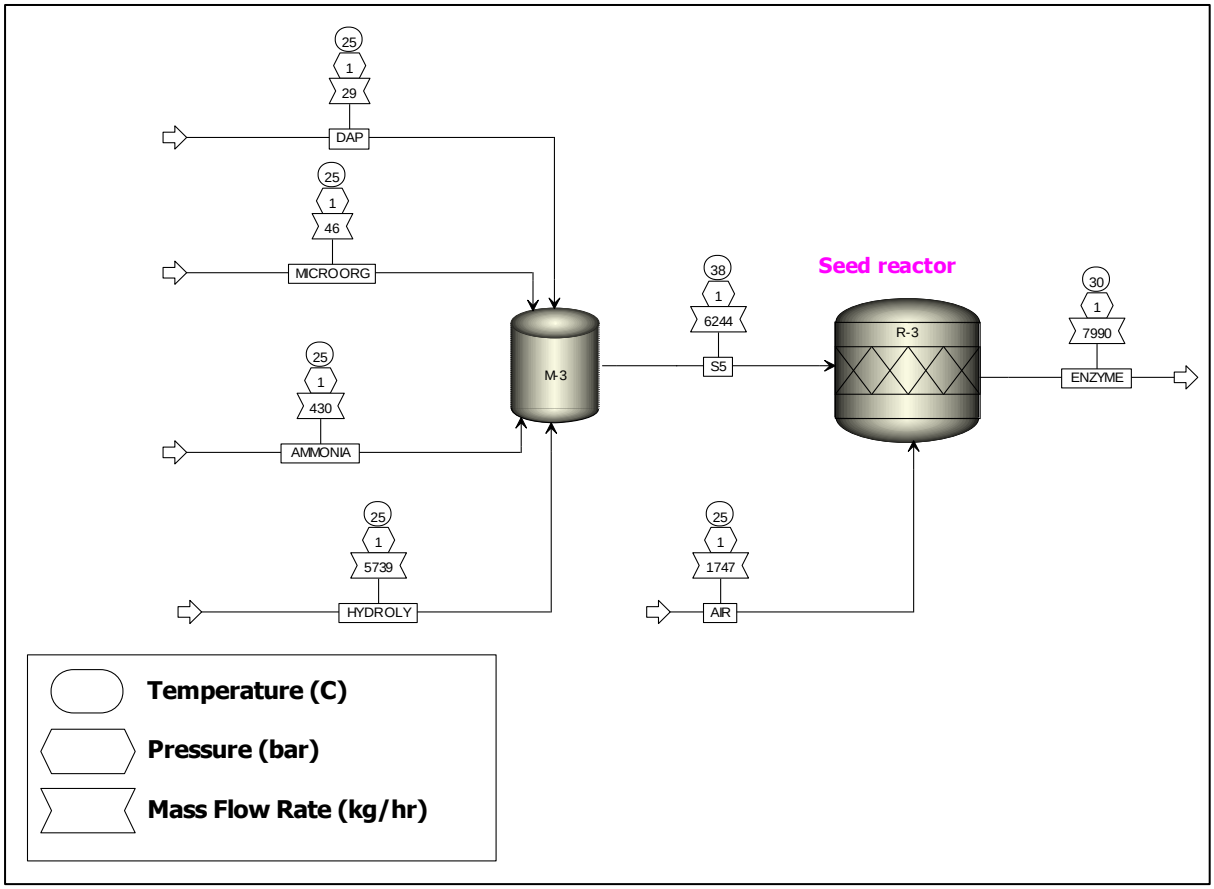

Figure 3-3: Aspen Plus flowsheet of enzyme production

Fermentation

The pre-treated slurry, enzyme, and ammonia are fed into the fermentation reactor, operating at 30 ℃ and at 15% solid loading. Simultaneous Saccharification and Fermentation (SSF) is adopted for this study. The pretreated slurry is converted to a fermentation broth containing ethanol, also called beer. The conversions in the fermentation reactor are as presented in Table 3-2 below (Moonsamy 2021).

Table 3-2: Conversion of the chemical reactions taking place in the fermentation reactor (Moonsamy 2021)

Reaction	Conversion
Cellulose to glucose $C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$	74.47%
Glucose to ethanol $C_6H_{12}O_6 \rightarrow 2\,C_2H_5OH + 2\,CO_2$	90.5%
Xylose to ethanol $3\,C_5H_{10}O_5 \rightarrow 5\,C_2H_5OH + 5\,CO_2$	76.56%

Carbon dioxide gas is removed from the fermentation broth prior to purification. The flash vapor from the pretreatment section is used to heat the fermentation broth. The heated fermentation broth is then sent to the flash and the water scrubber, where carbon dioxide is removed. During this process, some of the ethanol is lost to the vapour stream. Figure 3-4 present the flow sheet for fermentation.

Ethanol purification

The recovery section produces anhydrous ethanol. The fermentation broth is first fed to the distillation column, the product from the distillation column is further purified through the rectification distillation column, and finally through the molecular sieve. The beer column separates lignin and other heavy residues, yielding a 55 % ethanol distillate that is purified to 95 % in a rectifying column and ultimately 99.6 % in the molecular sieves. The entire recovery section loses 0.3 % of its ethanol to the residues (Moonsamy 2021). Figure 3-5 presents the flow sheet for ethanol purification.

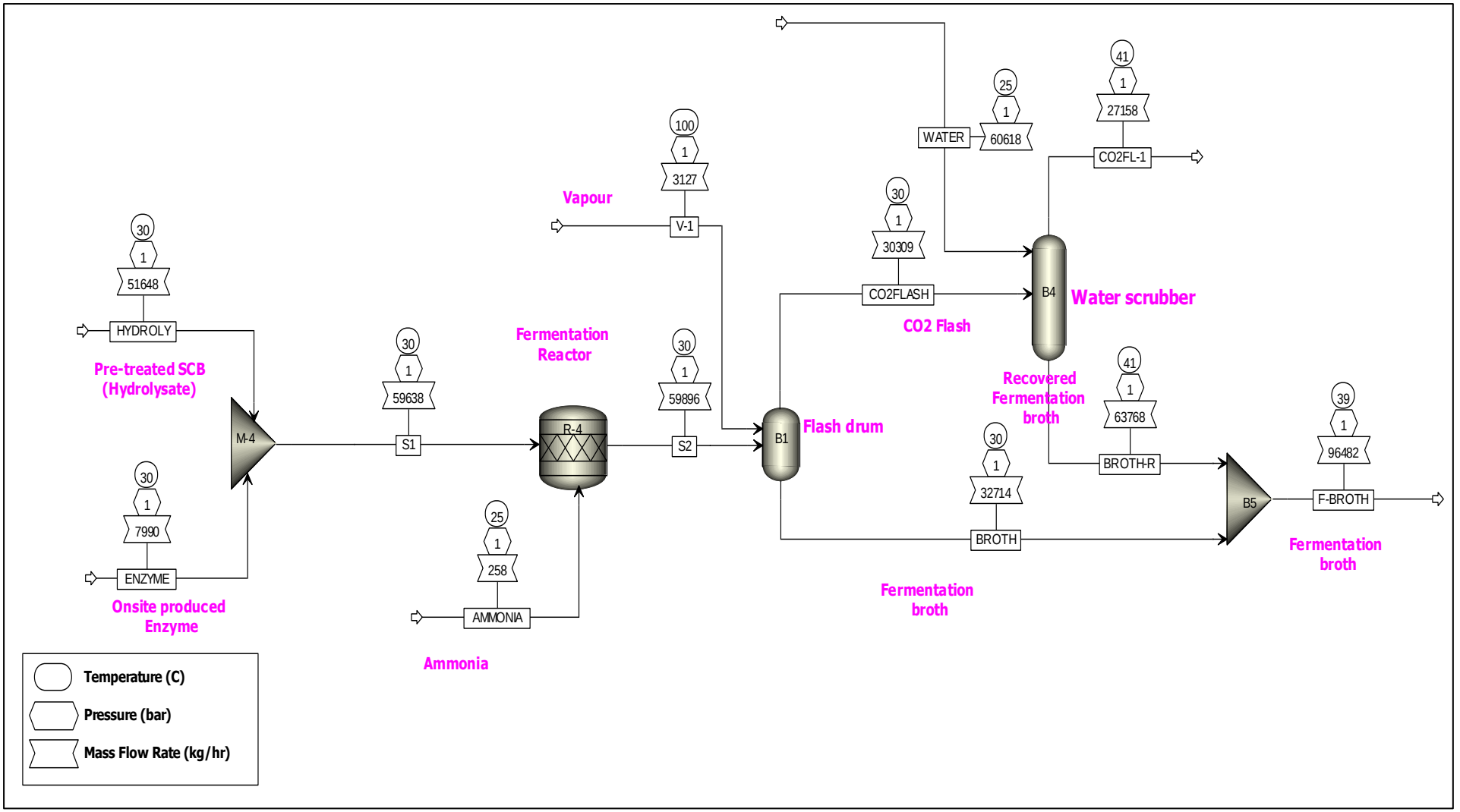

Figure 3-4: Aspen Plus flowsheet for fermentation

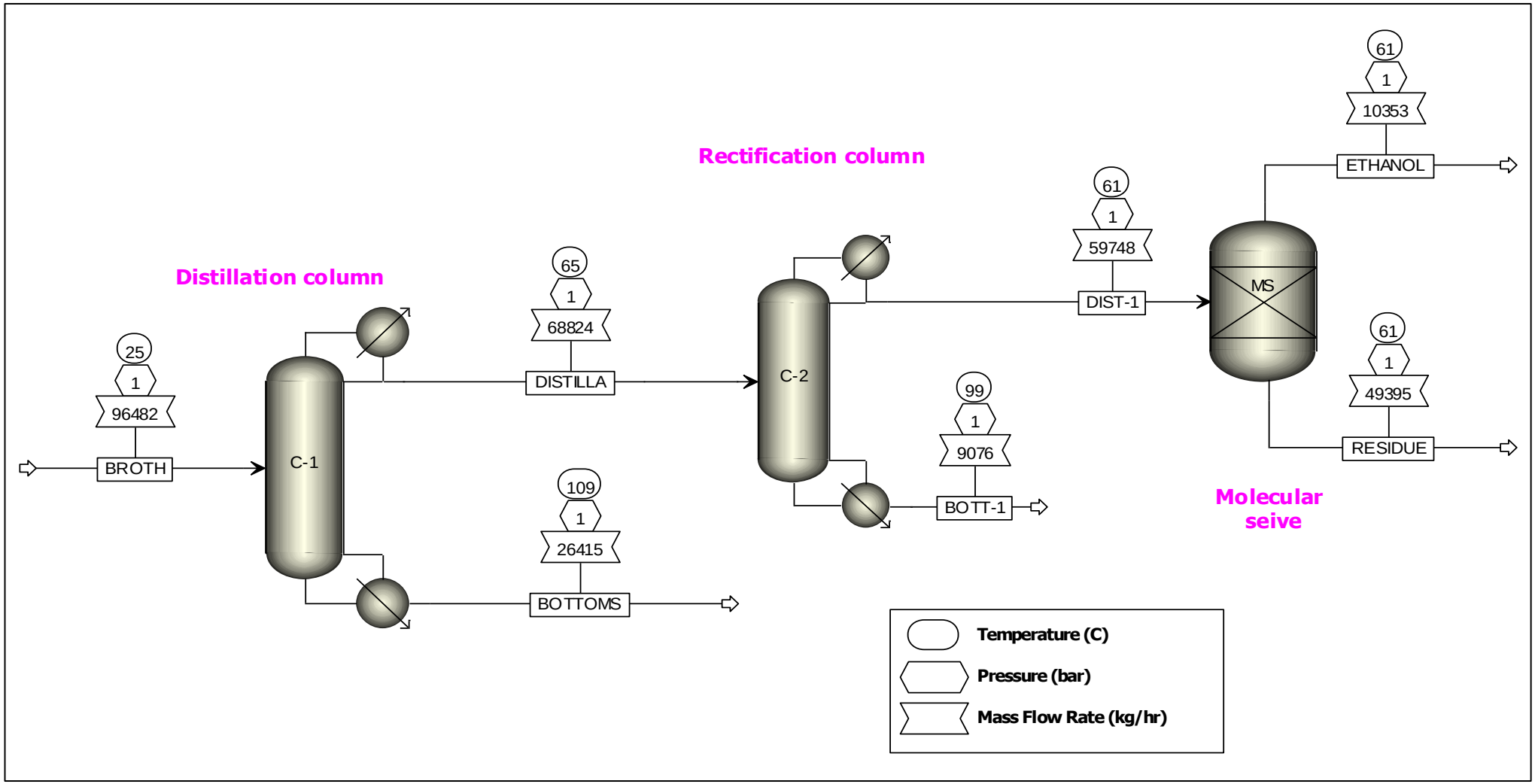

Figure 3-5: Ethanol purification Aspen Plus flowsheet

3.2.2. Anaerobic digestion

To access the sugar within the sugarcane bagasse, pre-treatment by steam explosion is required. The same simulation method as the one presented in the section for bioethanol is utilised. As in bioethanol, the NRTL property method is utilised together with the MIXNIC stream class, as in bioethanol production. The pre-treated slurry is fed into the digester, where acidogenesis, acetogenesis, and methanation take place and produce biogas and the by-product, digestate. Biogas consists of methane and carbon dioxide. The biogas produced is then purified to remove carbon dioxide. Simulation of the biogas biorefinery is further discussed in detail below.

Anaerobic digestion

The pre-treated slurry is fed into the digester, operating at 37 ℃ and 3 bar, where acidogenesis, acetogenesis, and methanation take place and produce biogas and the by-product, digestate. Biogas consists of methane and carbon dioxide, and other gases (Ravendran, Abdulrazik, and Zailan 2019a). Acidogenesis is the process whereby the simple sugars produced during pretreatment are converted to organic acids (volatile fatty acids), alcohols, aldehydes, carbon dioxide, and hydrogen. Acidogenesis was simulated using the R-stoic reactor, and the chemical reactions taking place in the reactor are presented in Table 3-2. The conversions were assumed to be 1 for all the chemical reactions (Kisiga 2024).

Table 3-3: Reactions taking place during Acidogenesis (Kisiga 2024)

Acidogenesis chemical reactions
Xylose → Methyl acetate + Acetic acid + carbon dioxide + Hydrogen $2C_5H_{10}O_5 \rightarrow C_3H_6O_2 + 3C_2H_4O_2 + CO_2 + H_2$
Glucose → Methyl acetate + Acetic acid + carbon dioxide + Hydrogen $C_6H_{12}O_5 \rightarrow C_3H_6O_2 + C_2H_4O_2 + CO_2 + H_2$

The products from acidogenesis undergo acetogenesis, whereby methyl acetate produced in the acidogenesis step is converted to acetic acid. Acetogenesis was simulated using the R-Stoic reactor, and the chemical reaction taking place in the reactor is presented in Table 3-4. The conversion was assumed to be 1 for the chemical reaction (Kisiga 2024).

Table 3-4: Reactions taking place during Acetogenesis (Kisiga 2024)

Acetogenesis chemical reaction
Methyl acetate + Water → Acetic acid + Carbon dioxide + Hydrogen $C_3H_6O_2 + 2H_2O \rightarrow C_2H_4O_2 + CO_2 + 3H_2$

The products from acetogenesis undergo methanogenesis for biogas production. Methanogenesis is the final step of anaerobic digestion, whereby acetic acid reacts with hydrogen to produce methane. Furthermore, the sulphur present reacts with hydrogen to form hydrogen sulfide, whereas nitrogen reacts with hydrogen to form ammonia. Methanogenesis was simulated using the R-Stoic reactor, and the chemical reactions taking place are presented in Table 3-5. The conversions for all the chemical reactions were assumed to be 1.

Table 3-5: Reactions taking place during Methanogenesis (Kisiga 2024)

Methanogenesis chemical reactions
Acetic acid + Hydrogen → Methane + Water $C_2H_4O_2 + H_2 \rightarrow CH_4 + H_2O$
Sulphur + Hydrogen → Hydrogen sulphide $S + H_2 \rightarrow H_2S$
Nitrogen + Hydrogen → Ammonia $N + H_2 \rightarrow NH_3$

The product of the anaerobic digester, which contains the mixture of methane, carbon dioxide, and traces of ammonia, hydrogen sulphide, and unconverted biomass, is sent to the liquid-solid separator, where the solid fraction (digestate) leaves at the bottom of the separator and is further used in the boilers for steam generation. The liquid fraction is heated to 53 ℃ and sent to the flash separator, where the gas is removed from the water. The flash operates at 53 ℃ and 1 bar (Ravendran, Abdulrazik, and Zailan 2019a). Biogas is purified using adsorption on activated carbon, where carbon dioxide, hydrogen sulfide, and ammonia are removed from biogas (Naqi, Kuhn and Joseph 2019). Figure 3-6 presents the flow sheet for biogas production.

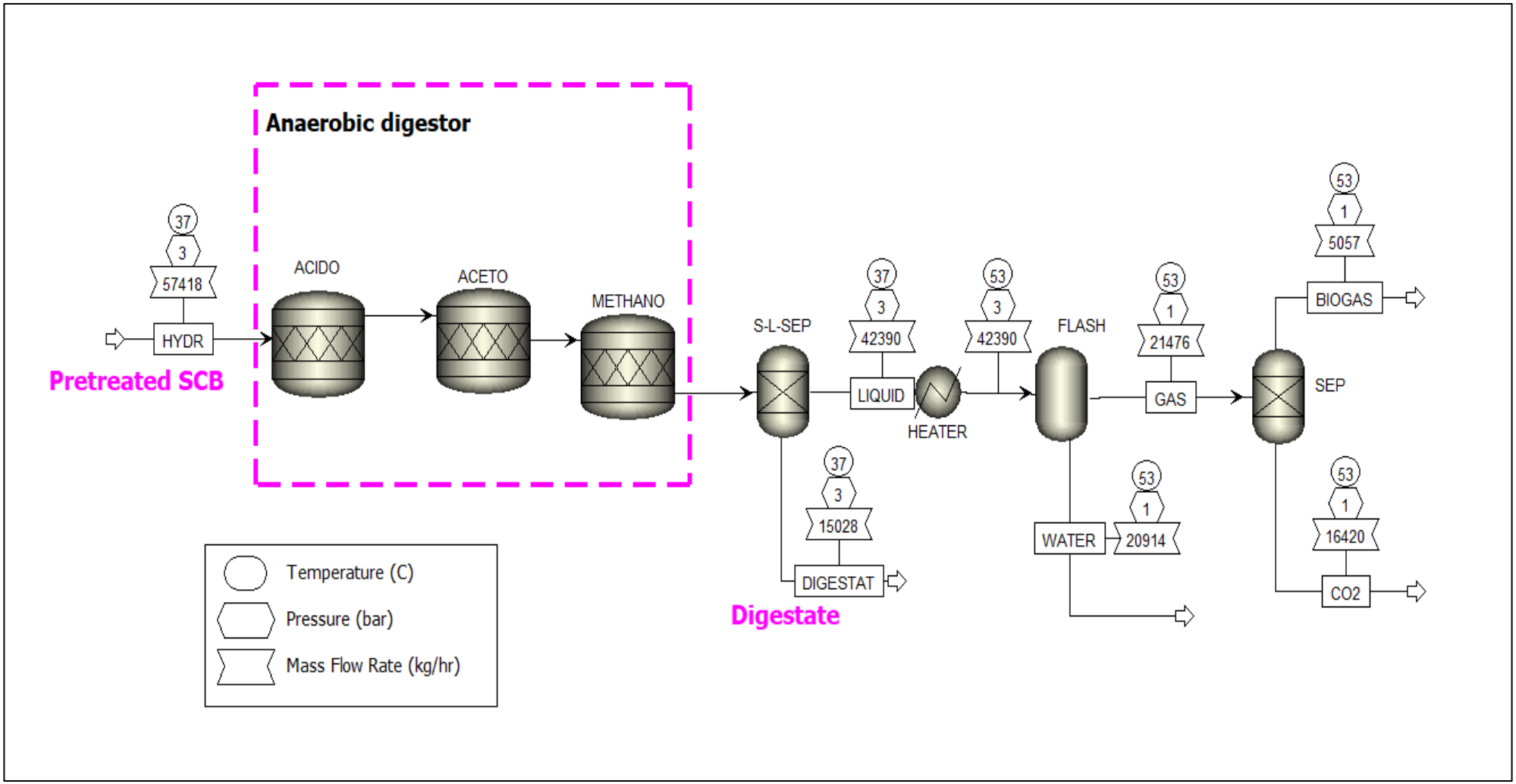

Figure 3-6: Biogas production Aspen Plus flowsheet

3.2.3. Dark fermentation

To access the sugar within the sugarcane bagasse, pre-treatment by steam explosion is required. The pre-treated slurry is fed into the fermentation reactor, where acidogenesis and acetogenesis take place and produce hydrogen gas and the by-product, digestate. The produced gas consists of a mixture of hydrogen, carbon dioxide, and volatile fatty acids (VFAs). Therefore, it requires downstream processing to purify and separate these gas components. It is then purified to remove carbon dioxide and VFAs. As in the previous two biological processing routes, the NRTL property method is utilised together with the MIXCINC stream class. Simulation of the biohydrogen biorefinery is further discussed in detail below. The simulation is similar to that of anaerobic digestion, except that biohydrogen does not have the methanogenesis step.

Dark fermentation

This scenario is developed based on the simulation for anaerobic digestion; however, for dark fermentation, the last step (methanogenic) is not present (Ravendran, Abdulrazik, and Zailan 2019a). Pretreatment (hydrolysis) adopted is the steam explosion, which is reported to be more effective in pre-treating sugarcane bagasse. It should be noted that pretreatment is the same across all the biological processing routes (i.e., bioethanol production, biogas production, and biohydrogen production). Therefore, for the simulation of this scenario, the output from the pretreatment simulation will be used. Figure 3-7 present the flow sheet for dark fermentation.

The sludge from the water and wastewater treatment plant is fed to the fermentation reactor as the inoculum. This helps in promoting the *Clostridium* bacteria, which are the main hydrogen-producing species. The *Clostridium* bacteria promote biohydrogen production. About 10% of the feed volume of sludge is added. This sludge is assumed to be prepared for processing, i.e., it has already undergone the removal of methanogenic bacteria. It should be noted that the sludge was not included in the simulation.

In the dark fermentation reactor, the feed undergoes acidogenesis and acetogenesis. The pre-treated slurry is fed into the fermentation reactor operating at 37 ℃ and 3 bar, where acidogenesis and acetogenesis take place and produce biohydrogen and the by-product, digestate (Ravendran, Abdulrazik, and Zailan 2019a). Acidogenesis is the process whereby the simple sugars produced during pretreatment are converted to organic acids (volatile fatty acids), alcohols, aldehydes, carbon dioxide, and hydrogen. Acidogenesis was simulated using

the R-stoic reactor, and the chemical reactions taking place in the reactor are presented in Table 3-6 . The conversions were assumed to be 1 for all the chemical reactions (Kisiga 2024).

Table 3-6: Reactions taking place during Acidogenesis (Kisiga 2024)

Acidogenesis chemical reactions
Xylose → Methyl acetate + Acetic acid + carbon dioxide + Hydrogen $2C_5H_{10}O_5 \rightarrow C_3H_6O_2 + 3C_2H_4O_2 + CO_2 + H_2$
Glucose → Methyl acetate + Acetic acid + carbon dioxide + Hydrogen $C_6H_{12}O_5 \rightarrow C_3H_6O_2 + C_2H_4O_2 + CO_2 + H_2$

The products from acidogenesis undergo acetogenesis, whereby methyl acetate produced in the acidogenesis step is converted to acetic acid, carbon dioxide, and hydrogen. Acetogenesis was simulated using the R-Stoic reactor, and the chemical reaction taking place in the reactor is presented in Table 3-7. The conversion was assumed to be 1 for the chemical reaction (Kisiga 2024).

Table 3-7: Reactions taking place during Acetogenesis (Kisiga 2024)

Acetogenesis chemical reaction
Methyl acetate + Water → Acetic acid + Carbon dioxide + Hydrogen $C_3H_6O_2 + 2H_2O \rightarrow C_2H_4O_2 + CO_2 + 3H_2$

The product of the fermentation reactor, which contains the mixture of hydrogen, acetic acid, carbon dioxide, and traces of water and unconverted biomass, is sent to the liquid-solid separator, where the solid fraction (digestate) leaves at the bottom of the separator and is further used in the boilers for steam generation. The liquid fraction consists of acetic acid, which does not further decompose in dark fermentation. To increase the economic feasibility of dark fermentation, acetic acid can be recovered from the liquid, using liquid -liquid extraction in the presence of a solvent. About 61-98% acetic acid can be recovered using 20% trioctylphosphine oxide in kerosene as a solvent, which is assumed to be recovered on a daily basis, meaning the solvent is recycled for one day, then discarded. The solvent to fermentation broth ratio is 0.33 (Alkaya *et al.* 2009).To simulate acetic acid recovery, the separator was used, where about 61% is assumed to be recovered, which is the minimum of the stated recovery range (Alkaya *et al.* 2009; Atasoy *et al.* 2018). The liquid fraction is heated to 53 ℃ and sent to the flash separator, where the gas is removed from the water. The flash operates at 53 ℃ and 1 bar (Ravendran,

Abdulrazik, and Zailan 2019a). Biohydrogen is purified using adsorption on activated carbon, where carbon dioxide is removed from biohydrogen (Naqi, Kuhn, and Joseph 2019). Figure 3-7 presents the flow sheet for biohydrogen production.

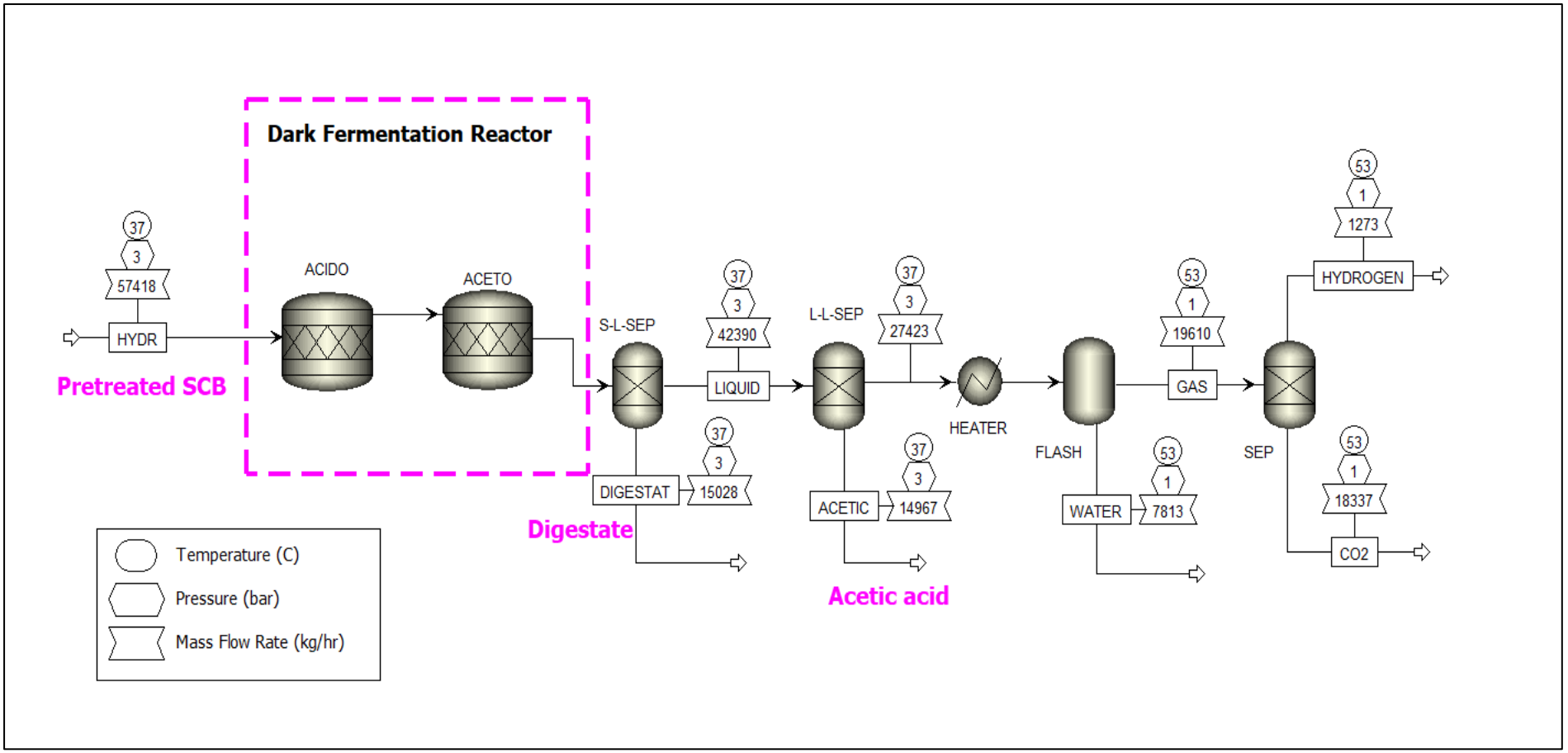

Figure 3-7: Dark fermentation Aspen Plus flowsheet

3.2.4. Gasification

Biomass and ash were simulated as non-conventional components and specified based on their ultimate and proximate analyses. DCOALIGT and HCOALGEN models in Aspen Plus were used to calculate the density and enthalpy of non-conventional components. Table 3-8 displays sugarcane bagasse proximate and ultimate properties such as Ash Content (AC), volatile Matter (VM), Fixed Carbon (FC), and elemental composition (C, H, O, N, and S), which were used for simulating this scenario. The Peng-Robinson equation of state was used as the global property method for the simulation.

Table 3-8: Bagasse proximate and ultimate analyses (Raveendran, Ganesh, and Khilar 1995)

Ultimate analysis	**(%wt, dry)**
C	48.1
H	4.55
O	43.15
S	0
Cl	0
Ash	3
Proximate analysis	**(%wt, dry)**
Volatile Matter	80.5
Fixed carbon	16.2
Ash	3.3

Drying, pyrolysis, combustion, and char gasification are the four phases of the biomass gasification process. Moisture content (MC) in fresh biomass feedstock is typically 50%. Therefore, the feedstock must be pre-dried in order to minimize the acceptable level of moisture content before feeding it into the gasifier. Drying takes place at a temperature of 109.85 ℃. The pyrolysis process is then carried out on the dried biomass. In this stage, the biomass feedstock thermally decomposes into volatiles, char, ash, and tar in the absence of air. Following Pyrolysis is the combustion of char with steam. The primary reaction occurring in a gasifier is combustion, which takes place at a temperature of 800 °C and supplies all the thermal energy needed to power the endothermic reactions (Kombe *et al.* 2022). When steam is introduced, the combustible components of the feedstock undergo gasification reactions, producing synthesis gas primarily composed of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). In the gasification zone, the leftover char eventually reacts with the combustion by-products. Numerous endothermic processes happen in this zone. The steam

flow rate was changed until all of the carbon (char) had volatilized. The carbon was completely volatilised at the steam flow rate of 14280 kg/hr, giving the steam to biomass ratio of 0.275. The combination of these gases is called the synthesis gas, shortened to syngas. For the purpose of removing the impurities in the gas mix, the gas is sent to the separator. Prior to separation, the gas is cooled to 45 ℃ (Jarungthammachote and Dutta 2008; Yang *et al.* 2009).

The sugarcane bagasse gasification process model flowsheet is presented in Figure 3-8. Table 3-9 presents a brief description of the Aspen Plus reactor blocks in the flowsheet, as well as a brief description of the default ID and an assigned ID, and a brief description of the function of each block. The default ID is a name defined by the software developer for a unit operation block, and the assigned ID is created by the user.

Table 3-9 : Description of simulation model blocks (Kombe *et al.* 2022)

Block ID	**Default block ID**	**Description**
DRYER	RStoic	Reduce the moisture content of the biomass using a stoichiometric reaction.
SEP	Sep	Separation of excess moisture from biomass.
DECOMP	Ryeid	Decomposing non - conventional biomass into conventional components based on ultimate and proximate analysis.
COMBUST	RGibbs	Simulate the partial oxidation and gasification of decomposed biomass components.
GASIFY	RGibbs	Simulate the reduction zone of the gasifier.
SOLIDSEP	Sep	Separate the unreacted char and ash from the syngas.
GASSEP	Sep	Syngas cleaning for the removal of water and other impurities.

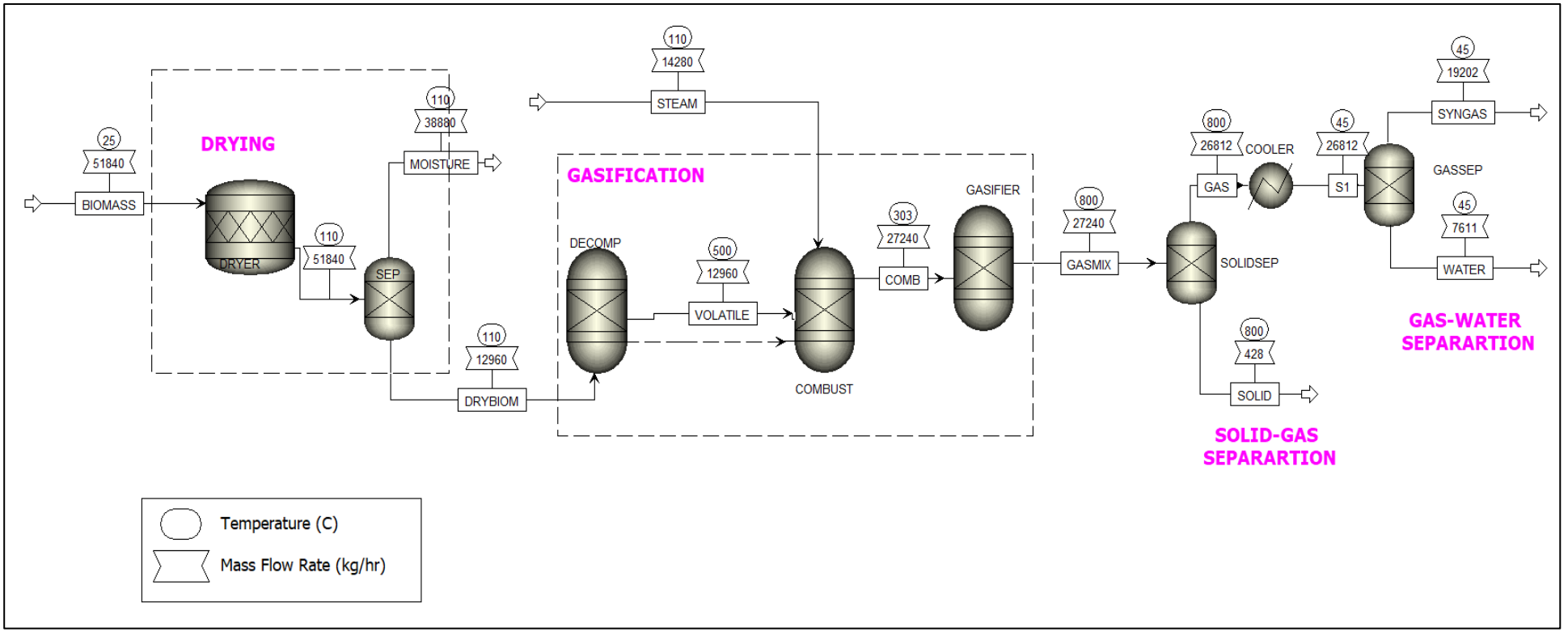

Figure 3-8: Gasification Aspen Plus flowsheet

3.2.5. Pyrolysis

Biomass and ash were simulated as non-conventional components and specified based on their ultimate and proximate analyses. DCOALIGT and HCOALGEN models in Aspen Plus were used to calculate the density and enthalpy of non-conventional components. Table 3-8 displays sugarcane bagasse proximate and ultimate properties such as Ash Content (AC), Volatile Matter (VM), Fixed Carbon (FC), and elemental composition (Carbon, Hydrogen, Oxygen, Nitrogen, and Sulphur), which were used for simulating this scenario. The Peng-Robinson equation of state with Boston-Mathias modifications (PR-BM) was used as the global property method for the simulation (Gorensek, Shukre, and Chen 2019). The Aspen Plus flowsheet for pyrolysis is presented in Figure 3-9.

Prior to pyrolysis, biomass, i.e., sugarcane bagasse, is dried to remove moisture content. Moisture content (MC) in fresh biomass feedstock is typically 50%. Therefore, the feedstock must be pre-dried in order to minimise the acceptable level of moisture content before undergoing pyrolysis. Drying takes place at a temperature of 100 ℃. The dryer is simulated using the heater and the separator, which makes it necessary to separate water from the biomass. The pyrolysis process is then carried out on the dried biomass. In this stage, the biomass feedstock thermally decomposes into its components as presented in Table 1-1, in the absence of air at a temperature of 500 ℃. The stage was simulated using the RYield reactor. Lignin was presented as oxygen-rich lignin, hydrogen-rich lignin, and carbon-rich lignin. The dried biomass is heated prior to the RYield reactor to increase the temperature of the biomass to 500 ℃.

The decomposed biomass enters two stoichiometric reactors where the biomass decomposition is further converted. The chemical reactions taking place in the first and second stoichiometric reactors are presented in Table 3-10 and Table 3-11 (Gorensek, Shukre, and Chen 2019). The description of the components and their specifications used in Aspen Plus is presented in the appendices. The components that were not available on the Aspen Plus database were defined using user-defined components by specifying the molecular weight, enthalpy of formation, heat capacity coefficients, and solid density. The properties are presented in appendices (Gorensek, Shukre, and Chen 2019).

The product stream from the second reactor undergoes solid-vapour separation in the cyclone. The cyclone was simulated using the separator in Aspen Plus. The vapour stream is cooled to 30 ℃ and sent to the condenser for the removal of non-condensable gases. These include hydrogen, carbon monoxide, and carbon dioxide. The liquid stream from the condenser is further treated for water removal to produce bio -oil.

Table 3-10: Chemical reactions taking place in the first stoichiometric reactor and their conversions (Gorensek, Shukre and Chen 2019)

Reaction	Conversion (%)
CELL → 0.4HAA + 0.05GLYOXAL + 0.15CH_3CHO + 0.25HMFU + 0.35ALD3 + 0.15CH_3OH + 0.3CH_2O + 0.61CO + 0.36CO_2 + 0.25H_2+ 0.93H_2O + 0.02HCOOH + 0.05C_3H6O_2 - N + 0.05CH_4 + 0.61CHAR	33.3
CELL → LVG	33.3
CELL → 5H_2O + 6CHAR	33.4
HCE → 0.35HCE1 + 0.65HCE2	100
LIGC → 0.35LIGCC + 0.1COUMARYL + 0.08PHENOL + 0.41C_2H_4 + H_2O + 1.02CO + 0.7H_2 + 0.3CH_2O + 0.495CH_4 + 5.735CHAR	100
LIGH → LIGOH + 0.5ALD3 + 0.5C_2H_4 + 0.2HAA + 0.1CO + 0.1H_2	100
LIGO → LIGOH + CO_2	100

Table 3-11: Chemical reactions taking place in the second stoichiometric reactor and their conversions (Gorensek, Shukre and Chen 2019)

Reaction	Conversion (%)
HCE1 → 0.6XYLAN + 0.2C3H6O_2 − N + 0.12GLYOXAL + 0.2FURFURAL + 0.4H_2O + 0.08H_2 + 0.16CO	50
HCE1 → 0.4H_2O + 0.8CO_2 + 0.05HCOOH + 1.6CO + 1.25H_2 + 0.3CH_2O + 0.625CH_4 + 0.375C_2H_4 + 0.875CHAR	50
HCE2 → 0.2H_2O + CO + 0.575CO_2 + 0.4CH_2O + 0.1C_2H_5OH + 0.05HAA + 0.35ACAC + 0.025HCOOH + 0.25CH_4 + 0.3CH_3OH+ 0.225C_2H_4 + 0.725H_2 + CHAR	100
LIGCC → 0.3COUMARYL + 0.2PHENOL + 0.35HAA + 0.7H_2O + 0.65CH_4 + 0.60C_2H_4 + 1.8CO + H_2 + 6.75CHAR	100
LIGOH → 0.21FE2MACR + 0.09ANISOLE + 0.09CH_3CHO + 0.24CH_2O + 1.36H_2O + 0.96CH_4 + 1.14CH_3OH + 1.5H_2+ 0.05CO_2+ 3.84CO + 0.05HCOOH + 0.65C_2H_4 + 0.025HMWL + 0.1ACROL + 7.4CHAR	100

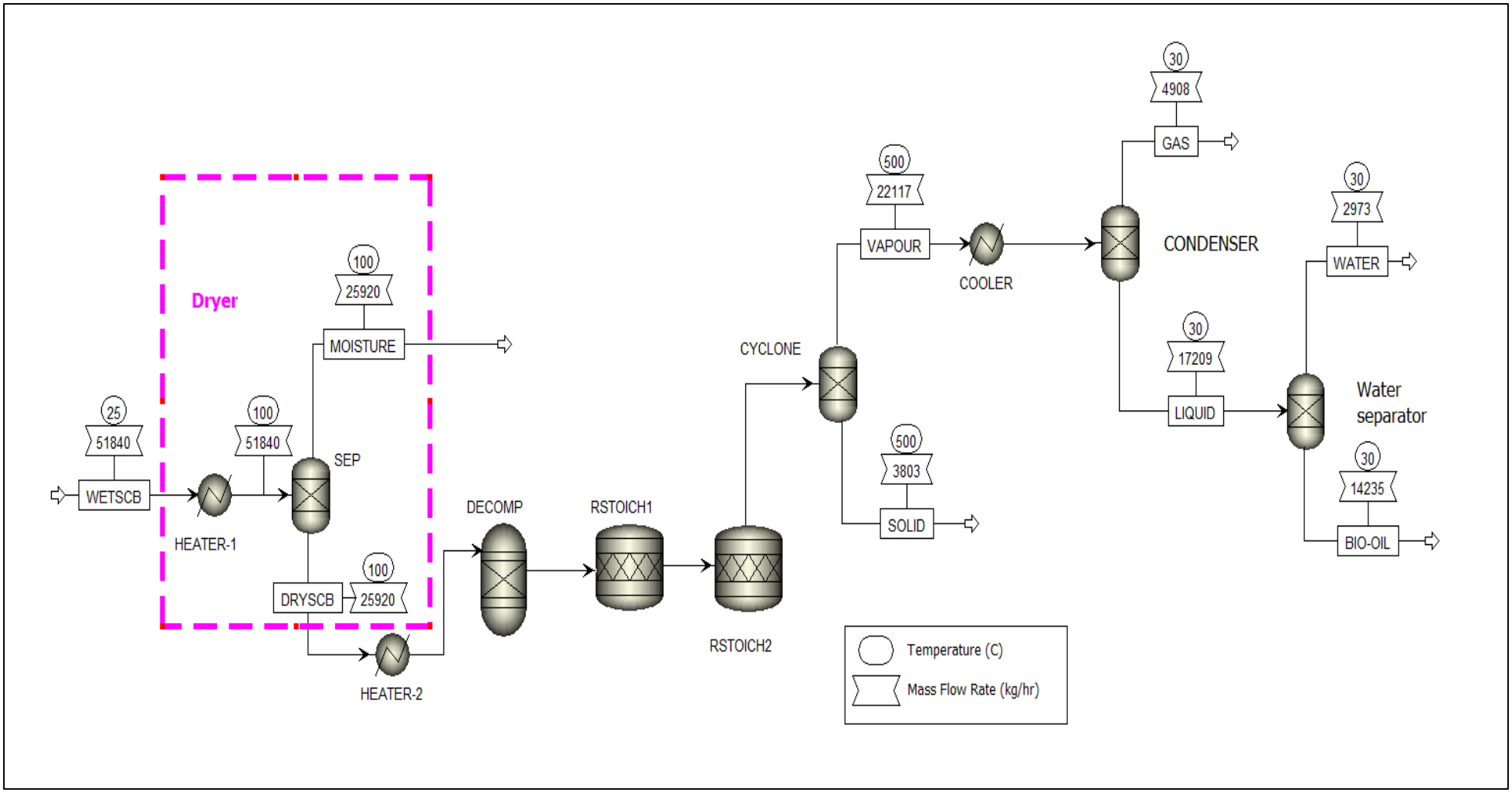

Figure 3-9: Fast pyrolysis Aspen Plus flow sheet

3.3. Economic assessment

This section gives a brief overview of how the economic assessment was performed. To identify economic performance drivers for the investigated process routes, the economic indicators were determined for each process route under investigation. Operating expenditure (OPEX), capital expenditure (CAPEX), and revenue or sales from each of the processing routes should be estimated to determine economic indicators. The economic assessment calculations were done using Microsoft Excel spreadsheets.

The economic parameters adopted in this study were selected based on standard Techno-economic assessment practices reported in the literature and aligned with industrial benchmarks applicable to chemical and biofuel production facilities. Plant lifetime, depreciation method, discount rate, operating hours, and working capital assumptions fall within ranges commonly applied in process engineering economic evaluations (Towler and Sinnott 2021). South African–specific parameters, including tax rate, exchange rate, and plant location, were selected to reflect the local economic and regulatory environment. Collectively, these assumptions ensure that the economic analysis is realistic, comparable to similar studies, and representative of industrial practice. The economic variables utilised in this study are outlined in Table 3-12.

Table 3-12: Economic parameters

Parameter	Value	References
Plant location	Sezela, KwaZulu-Natal, South Africa (Annexed to the sugar mill)	Site-specific assumption. Based on the location of the nearest sugar industry. Co-location with existing sugar mills is standard practice to reduce feedstock transport and capital costs in sugarcane biorefineries (Miranda *et al.* 2021; Moonsamy 2021).
Plant capacity	58140 kg/hr	Derived from a typical South African sugar mill crushing 300 t/h of cane, with ~270 kg bagasse/t cane (Miranda *et al.* 2021), and accounting for biomass bypass for energy generation.
Construction Period	2 years	Typical construction duration for medium-to-large chemical and bioenergy processing plants (Moonsamy 2021).
Plant life	25 years	Consistent with industry practice and commonly assumed lifetimes for bioenergy and chemical process plants (Moonsamy 2021).
Salvage value	$0	Conservative assumption widely adopted in techno-economic feasibility studies to avoid overestimation of profitability (Moonsamy 2021).

Operating hours	5000 hours/year	Reflects the seasonal operation of sugar mills in South Africa during the crushing season rather than year-round operation (Moonsamy 2021).
Depreciation	Straight-line over 5years @20%	Standard accounting practice in techno-economic assessments of process plants (Moonsamy 2021).
Project financing/Equity	100%	Simplified financing structure commonly assumed in preliminary techno-economic assessments (Moonsamy 2021).
Working capital	5%	Typical working capital requirement for chemical and biofuel processing plants reported in literature (Moonsamy 2021).
Discount rate	12%	Typical real discount rate used in techno-economic assessments of bioenergy and chemical process plants in South Africa and comparable emerging economies (Moonsamy 2021).
Tax rate	28%	South African corporate income tax rate applicable to industrial and energy projects during the study period (Moonsamy 2021).
Exchange rate	R18.36/USD	USD to ZAR Exchange Rate on 17 February 2025.
Chemical Engineering Plant Cost Index (CEPCI)	2019 - 607.5 2024 - 800.7	CEPCI values used to escalate capital cost data to the study year, following standard cost-updating methodology in chemical engineering economic analysis (Maxwell 2024).

The factorial method was utilised to conduct the economic assessment. This approach assesses expenses by considering the entire cost of all major equipment, while also considering expenses related to equipment installation, which are incurred in addition to equipment costs. These include pipes, buildings, lighting, coatings, and insulation materials for equipment elevation. Incorporating these factors results in what is known as the installed cost of equipment. The installed cost of equipment is defined as the Inside Battery Limit Investment (ISBL). All other costs are expressed in terms of ISBL investment (Towler and Sinnott 2021). The estimation of the costs is briefly explained in the following subsections, and the sample calculations are presented in Appendix F.

3.3.1. Capital expenditure

The total sum of fixed capital investment (FCI), working capital (WC), and start-up costs (SUC) is known as capital expenditure (CAPEX). The estimations of FCI, WC, and SUC are briefly explained below.

Fixed capital investment (FCI) refers to expenses related to planning, building, and constructing the plant. It is the total of the following: engineering costs (EC), contingency costs (CC), off-site plant costs (OSBL), and internal battery limit (ISBL). The factorial method was used to estimate the costs of the ISBL plant (Towler and Sinnott 2021).

Aspen Plus Economic Analyser was used to estimate the cost of the installed equipment for the simulated processes. Process simulations were developed in Aspen Plus V11, whose embedded equipment cost correlations are referenced to a 2019 cost basis, corresponding to the software release year. Consequently,2019 was adopted as the base year for the equipment cost estimation. The relevant chemical engineering plant cost index (CEPCI) is used to scale the installed equipment costs from the 2019 base year to the relevant economic analysis year, 2024. The scaled sum of installed equipment costs is equal to the internal battery limit (ISBL). The updated ISBL is estimated using the following equation:

Equation 3

$$\text{Scaled ISBL} = \text{installed plant cost (from Aspen)} \times \frac{\text{CEPCI 2024}}{\text{CEPCI 2019}}$$

From the calculated ISBL, other costs were estimated using the factorial method (Towler and Sinnott 2021) as follows:

- The off-site battery limit (OSBL) is estimated to be 40% of ISBL. OSBL includes costs that are related to the infrastructure, considering the plant expansions or modifications.
- The engineering cost (EC), which is the cost of engineering services needed during the course of the project, was estimated as 10% of the sum of ISBL and OSBL.
- The contingency costs (CC), which cater for unforeseen circumstances, were estimated as 10% of the sum of ISBL(Inside Battery Limits) and OSBL (Outside Battery Limits).

Working Capital (WC) refers to the funds utilised from the commencement of plant operations until the point at which the revenue generated from the sale of finished products can cover the ongoing expenses of the project. The WC (Working Capital) was calculated as 15% of the total sum of the ISBL (Inside Battery Limits) and OSBL (Outside Battery Limits) plant costs (Towler and Sinnott 2021).

Startup Costs (SUC) encompass the necessary expenses for budget planning, research, advertising, borrowing, as well as license and insurance charges. The SUC was estimated as 10% of the sum of ISBL (Inside Battery Limits) and OSBL (Outside Battery Limits) costs.

3.3.2. Operating expenses

Operating expenses (OPEX) are determined by considering the variable operating costs (VOC) and fixed operating costs (FOC). The variable operating costs encompass expenses related to feedstock, chemicals, and make-up water, and these costs vary from process to process. Fixed costs are costs that are not affected by the volume of production, this may include costs for renting, labour costs, etc. The estimation of the costs is briefly explained in the sections below:

Fixed costs

Fixed costs are estimated using the fractional method, with reference to the labour costs, ISBL costs, and OSBL costs. The labour costs (LC) were estimated using the following equation. The equation is based on the number of operators. It is assumed that the plant will be operating 24 hours with three 8-hour shifts per day. The calculation of the number of operators per shift was performed using the following equation (Towler and Sinnott 2021):

Equation 4

$$N_{OP} = (6.29 + 0.23\ N_{NP} + 31.7\ P^2)^{0.5}$$

Where:

$N_{OP} -$ Number of operators per shift

$N_{NP} -$ Number of non $-$ particulate processing units in the process

$P -$ Number of particulate processing units in the process

The number of operators was calculated using the above equation. The operator salary was assumed to be $2.35 per hour ($526.4 /month), which is the average operator pay in South Africa (Payscale 2024). The total fixed operating costs are estimated using the factorial method with reference to labour costs, inside battery limit (ISBL), and off-site plant cost (OSBL) (Towler and Sinnott 2021). Other costs are estimated as follows:

- The supervision costs are estimated as 25% of labour costs.
- Direct overhead costs are estimated as 40% of the sum of labour costs and supervision costs.
- Maintenance costs are estimated as 4% of inside battery limit (ISBL).
- Property taxes and insurance costs are estimated as 2% of inside battery limit (ISBL).
- General plant overhead is estimated as 65% of the sum of labour costs, supervision costs, direct costs, and maintenance costs.
- Rent will be assumed to be free as the plant will be annexed into the sugar mill; it is assumed that the land is available.
- Environmental charges were estimated as 1% of the sum of inside battery limit (ISBL) and off-site plant cost (OSBL).

Total Fixed costs are then calculated as the sum of the above costs.

Variable operating costs

Variable operating costs (VOC) are specific costs incurred in operating a plant that fluctuate based on the plant rate. Variable costs included the cost of raw materials, with sugar cane bagasse being the main raw material. Sugarcane bagasse (SCB) feed rate was constant for all the processes investigated. The SCB feed rate was 51840 kg/hr. The biorefineries are assumed to be annexed to the sugar mill, and SCB is assumed to be obtained for free from the sugar mill. Thus, the cost of the raw material, sugarcane bagasse, will be zero. The sugar mill is assumed to be located at Sezela, KwaZulu-Natal, South Africa. The SCB is transferred from the sugar mill to the biorefinery using the belt conveyors that were already in place for transferring SCB, which may be extended depending on the location of the biorefinery.

The area has waste sludge available from various treatment plants, and the sludge will be adopted as the raw material for biohydrogen production. The sludge will be obtained for free, however transportation costs will be incurred. The costs of other materials (consumables) required were estimated based on the prices from various sources, and online sources were mostly used. The consumables varied from process to process; consumables for biological processes involved ammonia, microorganisms for the production of the enzyme, and fermenting yeast, which was assumed to be produced onsite. Dark fermentation has an additional raw material, namely the solvent used for the recovery of acetic acid.

Utilities are also part of the variable operating costs. Utilities included electricity and water. Air requirements were also added as electricity costs, as air is produced using the compressor, which is assumed to be already available in the sugar mill. The electricity costs for other equipment, like distillation columns and heaters, were calculated by using the heat duties from Aspen Plus simulations. The heat duties were multiplied by the cost of electricity. The electricity cost in South Africa is $0.088 per kWh (Globalpetrolprices 2023).

The cooling tower is also assumed to be available on-site. Some processes required process water, and the cost of process water was determined based on the required process water as per Aspen Plus mass balances and the cost of industrial water. The cost of industrial water in eThekwini Municipality is $0,00307 per litre (EThekwiniMunicipality 2024). The cooling water requirements were estimated using the heat duty of the coolers and the temperature change using the following equation:

Equation 5

$$Q = \dot{m} c_p \Delta T$$

Where:-

$Q -$ the cooler heat duty (from Aspen plus simulations) (J/s).

$\dot{m} -$ the mass flowrate of water (kg/s).

$c_p -$ the specific heat capacity of water (J/kg. K).

$\Delta T -$ the change in temperature (K).

3.3.3. Total sales

The estimation of sales is dependent upon the sales of products for each processing route, which is determined by the annual operating hours, production rate, and selling prices.

3.3.4. Gross profit

Gross profit refers to the net profit obtained by a business after deducting all expenses associated with the production and sale of its goods or services. Gross profit was estimated by subtracting the cost of operating expenses from the total sales.

3.3.5. Cash flow analysis

The economic parameters used are summarised in Table 3-12. The plant design is assumed to be one year and this is assumed to be year, and it is assumed to be 2023, and the construction period is assumed to be 1 year with the start of construction being in 2024. The plant is assumed to be starting operations in the year 2025. The plant life is assumed to be 25 years for all scenarios. Furthermore, it was assumed that the plant operated at full capacity during its life, up until 2048 (25 years). The depreciation expenses were calculated as 20% of the gross profit. The taxable income was then calculated by subtracting the depreciation expenses from the gross profit. The payable tax was then calculated to be 28% of the taxable income, where 28% is the South African tax rate. The net cash flow was calculated by subtracting the tax payable from the gross profit. As presented in Table 3-12, the discount rate is 12%. However, the tax rate during plant construction was assumed to be 1%. The discounted cash flow was then calculated using the equation below, adopted from Thoppil and Zein (2021).

Equation 6

$$\mathrm{DCF_n} = \frac{\mathrm{CF_n}}{(1+\mathrm{i})^{\mathrm{n}}}$$

Where:-

$\mathrm{DCF_n}$ – the iscounted cash flow in year n

$\mathrm{CF_n}$ – the net cash flow in year n

i – the discount rate

3.3.6. Economic feasibility indicators

Four economic feasibility indicators were calculated, including payback period (PBP), rate of return on investment (ROI), net present value (NPV), and profitability index (PI).

The payback period was calculated using the equation below.

Equation 7

$$\text{Payback Period} = \frac{\text{Total investment}}{\text{Average annual net cash flow}}$$

The rate of return on investment is calculated using the following equation:

Equation 8

$$\text{ROI} = \frac{\text{Net annual Profit}}{\text{Total investment}}$$

The ROI is calculated at the end of the life of the project.

The net present value (NPV) is calculated as the sum of the discounted cash flow throughout the project life.

The profitability Index was calculated using the

following equation:

Equation 9

$$\text{Profitability Index} = \frac{\text{Net present value (NPV)}}{\text{Capital expenditure (CAPEX)}}$$

3.4. Lifecycle Assessment (LCA)

3.4.1. Goal and scope definition

The objective of performing the life cycle assessment for this study was to determine the most environmentally friendly processing route for processing sugarcane bagasse to biofuels amongst the five processes under investigation (bioethanol fermentation, anaerobic digestion, dark fermentation, gasification, and pyrolysis). In this study, the LCA was performed for the cradle-to-gate system boundary, which involves raw materials until the factory gate. In this study, for each scenario, the cradle will be sugarcane bagasse, which is a by-product of the sugar manufacturing process, and the gate is the biorefinery. The amount of sugarcane bagasse processed was used as the functional unit. The hourly throughput used in process simulations was used as the mass of sugarcane bagasse processed, which is 51840 kg of sugarcane bagasse (Cespi 2024). SimaPro software was used to perform LCA.

In LCA studies involving multiple outputs, system expansion using the avoided burden approach is often applied to account for products that may substitute conventional alternatives. However, this approach was not adopted in the present study. The primary objective of the LCA was a comparative assessment of biofuel production routes rather than an evaluation of substitution effects in external markets. Furthermore, the avoided burden approach requires assumptions regarding displaced products and market conditions, which may introduce additional uncertainty. Therefore, co-products generated during the biofuel conversion processes were treated using a mass-based allocation method, ensuring consistency and comparability across all scenarios in accordance with ISO 14044 guidelines.

The biorefinery was modelled as an independent facility, and no sharing of utilities such as steam, electricity, water, or chemicals with the sugar mill was assumed. All utility requirements were therefore fully attributed to the biofuel production system.

3.4.2. Life Cycle Inventory (LCI) Analyses

In the LCI analysis, the environmental inputs and outputs associated with the production processes under investigation were modelled in SimaPro release 9.6.0.1. In SimaPro, the Ecoinvent v3 database was utilised in this study. Ecoinvent is the database that consists of the data from various sectors, which include the production of chemicals, energy production, metal

production, transport, building materials, and fruit and vegetables. The inputs included raw materials and energy, while outputs included the products, emission of pollutants, and the waste streams. These were entered based on Aspen Plus mass balances for the processes under investigation. This enables the comparison of the environmental impact for processes under investigation in the Life Cycle Impact Assessment stage. The materials that were not available on SimaPro were created using the materials that are related to them. The medium voltage electricity was utilised for the electricity needs for all five scenarios. In SimaPro, medium voltage electricity is allocated to users, whereas high voltage electricity is applicable to big power plants.

3.4.3. Life Cycle Impact Assessment (LCIA)

The LCIA stage involves drawing conclusions that allow better business decisions. This stage shows how sustainable the production processes are (Golsteijn 2020). The structure of impact assessment considered in this study is characterisation and damage assessment. The impact assessment was conducted for both mid-point and end-point. The ReCipe 2016 midpoint (H) was utilised for the characterisation. Characterisation presents the environmental impacts of all processes under consideration, translated to the impact categories. The ReCiPe 2016 Midpoint (H) life cycle impact assessment method was utilised for the characterisation of environmental impacts.

The goal of damage assessment is to create a damage category by combining a number of indicators that are associated with different impact categories. SimaPro has three damage categories: human health, ecosystem, and resources.

Under characterisation, eight (8) impact categories were assessed for the processes under investigation. The impact categories that were investigated in SimaPro are Global warming, Fine particulate matter formation, Marine eutrophication, Terrestrial acidification, freshwater eutrophication, Mineral resource scarcity, Fossil resource scarcity, and Water consumption. The impact categories were selected as they are most applicable to biofuels production (Kisiga, Chetty, and Rathilal 2024).

3.4.4. Results Interpretation

The LCA was performed to compare the environmental impacts of the processes under investigation with an aim of choosing the best performing process in terms of environmental impacts, i.e., the process with the least environmental impact. The results from the SimaPro simulations were exported from the software to the Excel spreadsheet. The graphs were drawn from the data for comparison.

Chapter 4: Results and Discussion

4.1. Introduction

This chapter presents and discusses the outcomes of the study. Material and energy balances for the investigated process routes were generated through process simulations and analysed using Microsoft Excel, and the corresponding results are presented in Section 4.2. Preliminary equipment cost estimates obtained from Aspen Capital Cost Estimator are also presented, forming the basis for the techno-economic assessment of the process routes. The economic assessment results are discussed in Section 4.3. In addition, the life cycle assessment (LCA), conducted using SimaPro and Microsoft Excel, is presented in Section 4.4.

4.2. Overall mass and energy requirements

Mass and energy balances are the primary technical data obtained from each process simulation. The performance of the various scenarios is compared using results such as biofuel production yields, concentrations, as well as heating, cooling, and power demands. This section presents the results of the mass and energy balance calculations performed in Microsoft Excel. The calculations were based on simulation stream results extracted from Aspen Plus process simulations for each process under investigation. This section is critical for determining process mass flows, energy efficiency, and other important parameters. Furthermore, these process parameters indicate the potential of each process, while also allowing for the tracking of material flow through the system. The Aspen simulation reports are available in Appendix B, while the simulation file access link is available in Appendix G.

All scenarios were assumed to have the same amount of feedstock available for the biorefinery, namely 51 840 kg/hr of sugarcane bagasse. A measure of biofuel production per tonne of biorefinery feedstock is useful for determining overall process yields and identifying the scenarios and processes that result in high biofuel production. The main products considered include ethanol (fermentation), methane (anaerobic digestion), biohydrogen (dark fermentation), syngas and biochar (gasification), and bio-oil, syngas, and biochar (pyrolysis).

The overall mass balance was performed for the five processes under investigation. An error analysis was conducted for each scenario to determine whether any major errors occurred during process simulation with respect to stream mass flows. The biochemical processing

routes (fermentation, anaerobic digestion, and dark fermentation) required pre-treatment, which utilised steam, as steam explosion was applied as the pretreatment method. This resulted in significant water usage in the biochemical processing routes. Water was also required for slurry preparation prior to fermentation. In contrast, the thermochemical processing routes required biomass pre-drying rather than pretreatment. No water was used in the pyrolysis process; however, gasification required water, since steam was used as the gasifying agent. This resulted in the gasification process utilising 14 280 kg/hr of water.

The material balance for bioethanol production is presented in Table 4-1, where the process inputs and outputs are shown. During biomass pre-treatment, where steam explosion impregnated with sulphur dioxide was applied, approximately 259 kg/hr of sulphur and 1233 kg/hr of air were utilised to produce sulphur dioxide on-site. Approximately 2076 kg/hr of air was used in enzyme production.

Cellulase enzyme for enzymatic hydrolysis was produced on-site. Enzyme production used 10% of the pretreated slurry and required nutrients such as diammonium phosphate (DAP) (29 kg/hr), ammonia (688 kg/hr), microorganisms (46 kg/hr), and a hydrolysate fraction. Saccharomyces cerevisiae (S. cerevisiae) was used in this study. During ethanol purification, the water scrubber utilised 60618 kg/hr of water to remove CO_2, making bioethanol production water-intensive. Approximately 10353 kg/hr of bioethanol was produced, together with about 9582 kg/hr of condensate, which was reused in the biorefinery. Approximately 13531 kg/hr of stillage was produced, which was also reused as a fuel in the boiler for steam generation.

Table 4-1: Overall mass balance for the fermentation process (bioethanol production)

Inputs		**Outputs**	
Stream	**Mass (kg/hr)**	**Stream**	**Mass (kg/hr)**
Sugarcane Bagasse	51840	Ethanol	10353
Lower Pressure steam	7212	CO_2 Flash	27158
Sulphur	259	Condensate	9582
Air	3309	Solid residue	3359
DAP	29	Rectification bottoms	9076
Ammonia	688	Molecular sieve residue	49395
Microorganism	46	Concentrated stillage	13531
Water	60618		
	124001		**122454**

Biogas production material balance is presented in Table 4-2, where the process inputs and outputs are shown. During biomass pre-treatment, where steam explosion impregnated with sulphur dioxide was used, approximately 259 kg/hr of sulphur and 1233 kg/hr of air were utilised to produce sulphur dioxide on-site. About 7212 kg/hr of steam was used during the steam explosion pre-treatment stage. The anaerobic digestion process resulted in the production of 5057 kg/hr of methane, 16420 kg/hr of CO2, 20914 kg/hr of wastewater, and 15028 kg/hr of digestate. Wastewater was generated during the flashing of the produced gas; this water originated from the moisture content of the feedstock and the steam supplied during steam explosion.

Table 4-2: Overall mass balance for the anaerobic digestion process

Inputs		**Outputs**	
Stream	**Mass (kg/hr)**	**Stream**	**Mass (kg/hr)**
Sugarcane Bagasse	51840	Methane	5057
Lower Pressure steam	7212	CO_2	16420
Sulphur	259	Water	20914
Air	1233	Digestate	15028
	60544		**57419**

Biohydrogen production material balance is presented in Table 4-3, where the process inputs and outputs are shown. During biomass pre-treatment, where steam explosion impregnated with sulphur dioxide was used, approximately 259 kg/hr of sulphur and 1233 kg/hr of air were utilised to produce sulphur dioxide on-site. About 7212 kg/hr of steam was used during steam explosion pre-treatment. The dark fermentation process resulted in the production of 1273 kg/hr of hydrogen, 14967 kg/hr of acetic acid, 18337 kg/hr of CO_2, 15028 kg/hr of digestate, and 7813 kg/hr of water.

Table 4-3: Overall mass balance for the dark fermentation process

Inputs		**Outputs**	
Stream	**Mass (kg/hr)**	**Stream**	**Mass (kg/hr)**
Sugarcane Bagasse	51840	Biohydrogen	1273
Lower Pressure steam	7212	Acetic acid	14967
Sulphur	259	CO_2	18337
Air	1233	Digestate	15028
		Water	7813
	60544		**57418**

Gasification process material balance is presented in Table 4-4, where the process inputs and outputs are shown. The inputs to the process were 51840 kg/hr of biomass together with 14280 kg/hr of steam, which acted as the gasifying agent. The outputs of the gasification process were syngas (a mixture of

hydrogen and carbon monoxide), solid char (428 kg/hr), and water (46491 kg/hr), which was removed from the gas stream as well as moisture removed during biomass pre-drying.

Table 4-4: Overall mass balance for the gasification process

Inputs		**Outputs**	
Stream	**Mass (kg/hr)**	**Stream**	**Mass (kg/hr)**
Sugarcane Bagasse	51840	Syngas	19202
Steam	14280	Water	46491
		Solid (char)	428
	66120		**66121**

The pyrolysis process material balance is presented in Table 4-5, where the process inputs and outputs are shown. The input to the pyrolysis process was 51840 kg/hr of biomass only, unlike the other processes. The outputs of the pyrolysis process were bio-oil (14235 kg/hr), solid char (3803 kg/hr), gas stream (4908 kg/hr), and water (28893 kg/hr). Pyrolysis produced three useful products, which include bio-oil, syngas (gas stream), and biochar (solid char). In terms of yield percentages, fast pyrolysis produced 60% bio-oil, 16.57% biochar, and 23.43% syngas.

Table 4-5: Overall mass balance for the pyrolysis process

Inputs		**Outputs**	
Stream	**Mass (kg/hr)**	**Stream**	**Mass (kg/hr)**
Sugarcane Bagasse	51840	Bio-oil	14235
		Solid (char)	3803
		Gas	4908
		Water	28893
	51840		**51839**

The main biofuel product yield for each process scenario is presented as the amount of biofuel produced per tonne of sugarcane bagasse, and the results are shown in Figure 4-1. This is also referred to as the mass ratio; it presents the production yields of the investigated process routes on a per-tonne basis. Fermentation has a mass yield of 0.2 tonnes of ethanol per tonne of SCB, which falls within the range of 0.15–0.30 tonnes of bioethanol per tonne of SCB previously reported (Mussatto *et al.* 2010; da Silva *et al.* 2016; Moonsamy 2021). Anaerobic digestion has a mass yield of 0.1 tonnes of methane per tonne of SCB, which is within the range of 0.10–0.20 tonnes of methane per tonne of SCB previously reported (Karthikeyan and Visvanathan 2013). Dark fermentation has a mass yield of 0.025 tonnes of biohydrogen per tonne of SCB; however, this is below the range of 0.10–0.20 tonnes of biohydrogen per tonne of SCB previously reported (Show *et al.* 2012). Dark fermentation also produces acetic acid as a by-product, which was not included in Figure 4-1 because it is not classified as a biofuel.

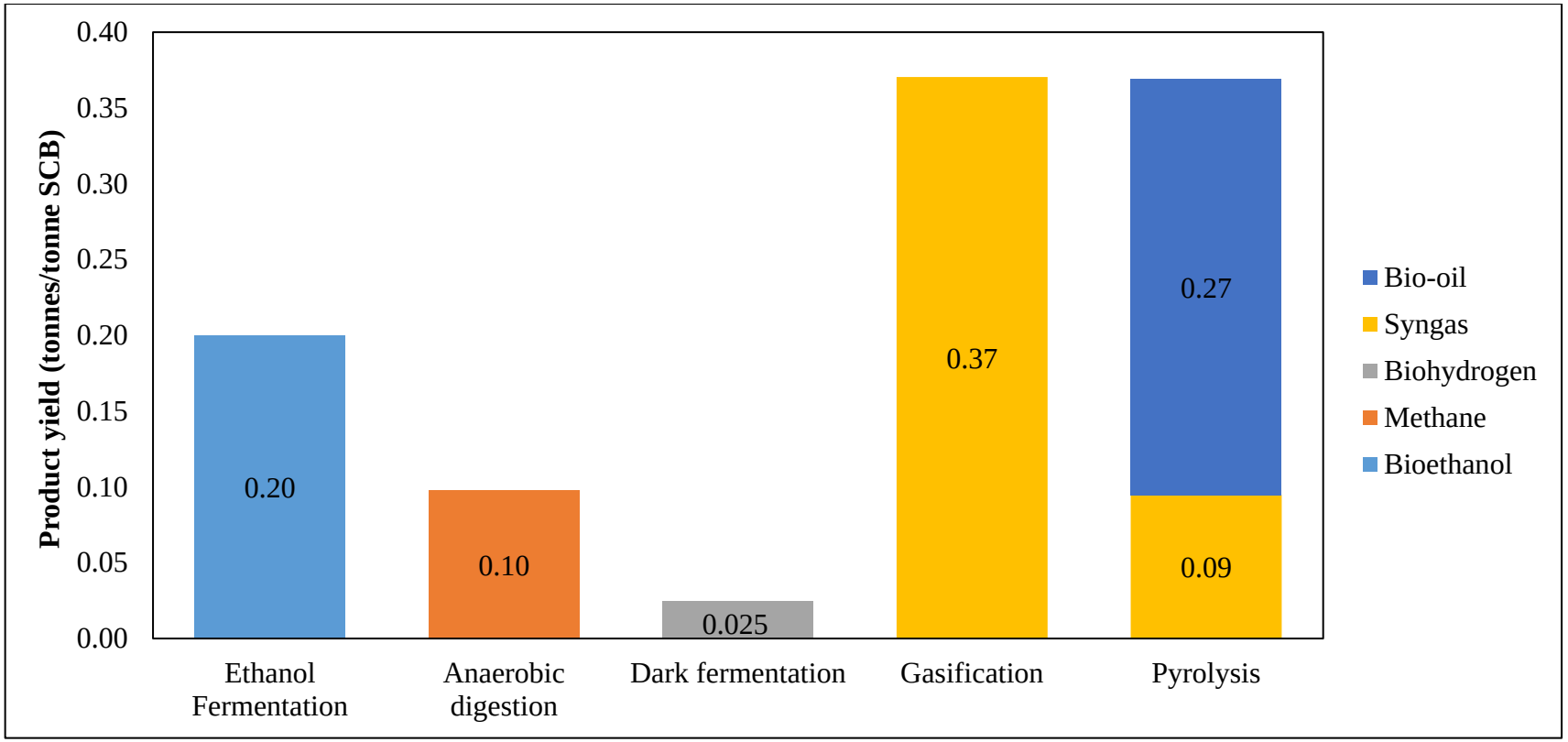

Figure 4-1: Biofuel product yields per tonne of sugarcane bagasse for the investigated biochemical and thermochemical conversion routes

Gasification produces two main products, syngas and biochar; however, only syngas was considered in the mass yield, as biochar is not classified as a biofuel. Gasification has a mass yield of 0.37 tonnes of syngas per tonne of SCB, which falls within the typical mass yield range of 0.35–0.55 tonnes of syngas per tonne of SCB previously reported (Gomez *et al.* 2010). Fast pyrolysis produces three products, namely bio-oil, syngas, and biochar; however, only bio-oil and syngas were considered in the mass yield. Pyrolysis has a combined mass yield of 0.36 tonnes of bio-oil and syngas per tonne of SCB, consisting of 0.27 tonnes of bio-oil and 0.09 tonnes of syngas per tonne of SCB. This value falls within the typical mass yield range of 0.25–0.40 tonnes of bio-oil and syngas per tonne of SCB previously reported (Patel, Zhang, and Kumar 2016). Overall, fast pyrolysis has proven to be the most productive method for biofuel recovery from sugarcane bagasse, followed closely by gasification.

Heating and cooling requirements for the investigated processing routes are presented in Table 4-6. Bioethanol production has the highest heating duty, followed by gasification, anaerobic digestion, biohydrogen production, and lastly pyrolysis. Ethanol production also shows a high cooling duty, followed by anaerobic digestion, gasification, biohydrogen production, and lastly pyrolysis. Pyrolysis appears to be more favourable, as it has the lowest heating and cooling duties.

Table 4-6: Heating and cooling requirements for the investigated production processes

Production Process	Heating Duty (MWh)	Cooling Duty (MWh)
Ethanol Fermentation	98.24	94.85
Anaerobic digestion	28.71	26.14
Dark Fermentation	28.80	14.68
Gasification	45.12	15.93
Pyrolysis	9.77	7.79

Bioethanol production stands out as the most energy-intensive process, requiring the highest heating and cooling duties. This is largely due to the distillation steps involved, as well as the pre-treatment stage, which requires heating sugarcane bagasse to 190 ℃. The fermentation process requires precise temperature control, while distillation is energy-demanding because it involves separating ethanol from water. The high cooling demand correlates with the heat generated during the fermentation and distillation steps, necessitating significant cooling requirements. The increased cooling duty is mainly due to the cooling that takes place after

pretreatment in order to reduce the biomass temperature to the optimum fermentation temperature of 30 ℃.

Biogas production and biohydrogen production require substantially less heating and cooling than bioethanol production. The main energy requirement in biogas and biohydrogen production arises from heating the reactors to maintain optimal temperatures for microbial activity, as well as pretreatment, which is in the form of steam explosion at 190 ℃. Acetic acid recovery through liquid-liquid extraction also adds to the energy demand in dark fermentation. Cooling demand is also present but lower due to the less exothermic nature of these processes. These two processes are closely related; therefore, they have similar energy requirements.

Gasification presents a moderate heating requirement, as it involves high-temperature processes that convert biomass into syngas. The heating duty for gasification is substantial due to biomass pre-drying, the high operational temperature required (800 ℃), and the use of steam as the gasifying agent. However, the cooling duty is relatively low. This is because gasification typically incorporates heat recovery, reducing the need for external cooling.

Pyrolysis requires less heating than gasification but still demands energy to heat biomass to 500 ℃ in the absence of oxygen. The cooling duty is also moderate, reflecting the need to control the temperature as volatile gases are condensed to form bio-oil.

Overall, bioethanol production is the most energy-demanding process in terms of both heating and cooling. In contrast, pyrolysis is significantly more energy-efficient. Gasification occupies an intermediate position, with a relatively high heating duty due to its high operating temperature and steam requirement.

4.3. Economic assessment

Economic assessment is a critical component in the evaluation of any production process, particularly in the context of bioenergy and renewable resources. This section presents the economic assessment results of the five investigated processing routes. The equipment costs, CAPEX, OPEX, total sales, and gross profit for the investigated processing routes are presented and discussed.

4.3.1. Equipment costs

After a successful simulation, the installed cost of all equipment was estimated using the Aspen Process Economic Analyser (APEA) in Aspen Plus. The software performs equipment mapping, sizing, and cost evaluation. Mapping is necessary, as some simulation blocks may not represent real equipment and must be removed or replaced with appropriate equipment from the model palette. Heat exchangers were mapped as shell-and-tube units for all coolers using cooling water. The software calculates equipment sizes based on mass and energy balances. APEA estimated both the unit and installed costs for all equipment across the investigated processing routes. The Chemical Engineering Plant Cost Index (CEPCI) was used to estimate ISBL investment by updating the installed cost of all equipment to 2024. A 2019 CEPCI was adopted as the base year, as the equipment cost correlations in Aspen Plus v11 are referenced to 2019, corresponding to the software release year (Detsios *et al.* 2024).

The installed equipment costs for Fermentation are presented in Table 4-7. The total installed equipment cost for fermentation amounts to 2.07 million USD, with the updated Inside Battery Limits (ISBL) cost reaching 2.73 million USD. Bioethanol production via fermentation involves multiple stages, such as pre-treatment, enzyme production, fermentation, and ethanol purification, with purification being the most expensive process step. The high costs are largely due to the complexity of the distillation and purification steps, which are also energy-intensive.

Table 4-7: Ethanol fermentation installed equipment costs

Process	**Total equipment installed costs (Million USD)**
Pre-treatment	$0.67
Enzyme Production	$0.21
Fermentation and flashing	$0.41
Ethanol Purification	$0.77
Total	**$2.07**

Total updated Inside Battery Limits (ISBL)	**$2.73**

Anaerobic digestion installed equipment costs are presented in Table 4-8. The anaerobic digestion process has a total installed equipment cost of 2.00 million USD, while the updated ISBL cost is 2.64 million USD. Anaerobic digestion and gas cleaning represent the largest cost components. Although the total cost is lower than that of bioethanol fermentation, anaerobic digestion still requires substantial investment, particularly in the gas cleaning stage, which ensures that the produced biogas meets the required quality standards for energy use.

Table 4-8: Anaerobic digestion production installed equipment costs

Process	**Total equipment installed costs (Million USD)**
Pre-treatment	$0.67
Anaerobic digestion and gas cleaning	$1.33
Total	**$ 2.00**
Total updated Inside Battery Limits (ISBL)	**$ 2.64**

Table 4-9 depicts the equipment costs for dark fermentation. Dark fermentation has a total installed equipment cost of 1.88 million USD and an updated ISBL cost of 2.47 million USD, indicating a lower capital investment compared to bioethanol fermentation and anaerobic digestion. The most significant investments are associated with the dark fermentation reactor, acetic acid recovery, and gas cleaning. The lower costs of dark fermentation reflect the relative simplicity of the process compared to the more complex bioethanol fermentation route; however, gas cleaning remains an essential and costly process step.

Table 4-9: Dark Fermentation installed equipment costs

Process	**Total equipment installed costs (Million USD)**
Pre-treatment	$0.67
Dark fermentation, Acetic acid recovery, and gas cleaning	$1.21
Total	**$1.88**
Total updated Inside Battery Limits (ISBL)	**$2.47**

Table 4-10 outlines the installed equipment costs for the gasification process. Gasification presents one of the lowest installed equipment costs at 0.70 million USD, with an updated ISBL cost of 0.92 million USD. The main process stages, including drying, gasification, and gas separation, are relatively less capital-intensive compared to the other investigated processing routes.

Table 4-10: Gasification installed equipment costs

Process	Total equipment installed costs (Million USD)
Drying	$0.26
Gasification	$0.23
Gas separation	$0.22
Total	**$0.70**
Total updated Inside Battery Limits (ISBL)	**$0.92**

Table 4-11 presents the installed equipment costs for pyrolysis. Pyrolysis has a total installed equipment cost of 0.97 million USD, with an updated ISBL cost of 1.27 million USD. The process includes multiple steps, such as drying, pyrolysis, solid–vapour separation, liquid–gas separation, and bio-oil recovery. The most costly process step is bio-oil and water recovery, indicating that while pyrolysis equipment costs are moderate, additional expenses are associated with refining and recovering useful products from the process.

Table 4-11: Pyrolysis installed equipment costs

Process	Total equipment installed costs (Million USD)
Drying	$0.10
Pyrolysis	$0.09
Solid vapour separation	$0.13
Ethanol Purification	$0.15
Liquid gas separation	$0.18
Bio-oil water recovery	$0.31
Total	**$0.97**
Total updated Inside Battery Limits (ISBL)	**$1.27**

Figure 4-2 shows a comparison of the installed equipment costs for the investigated process routes. The highest capital expenditure is observed for the fermentation process, with an installed equipment cost of 2.73 million USD. Anaerobic digestion follows, with an installed equipment cost of 2.64 million USD. The dark fermentation process, with an installed equipment cost of 2.47 million USD, requires a moderate capital investment compared to fermentation and anaerobic digestion. Gasification has the lowest installed equipment cost at 0.92 million USD, while pyrolysis has a moderate installed cost of 1.27 million USD. Although pyrolysis involves multiple stages, such as solid–vapour separation and bio-oil recovery, its

overall equipment cost remains lower than that of fermentation and anaerobic digestion.

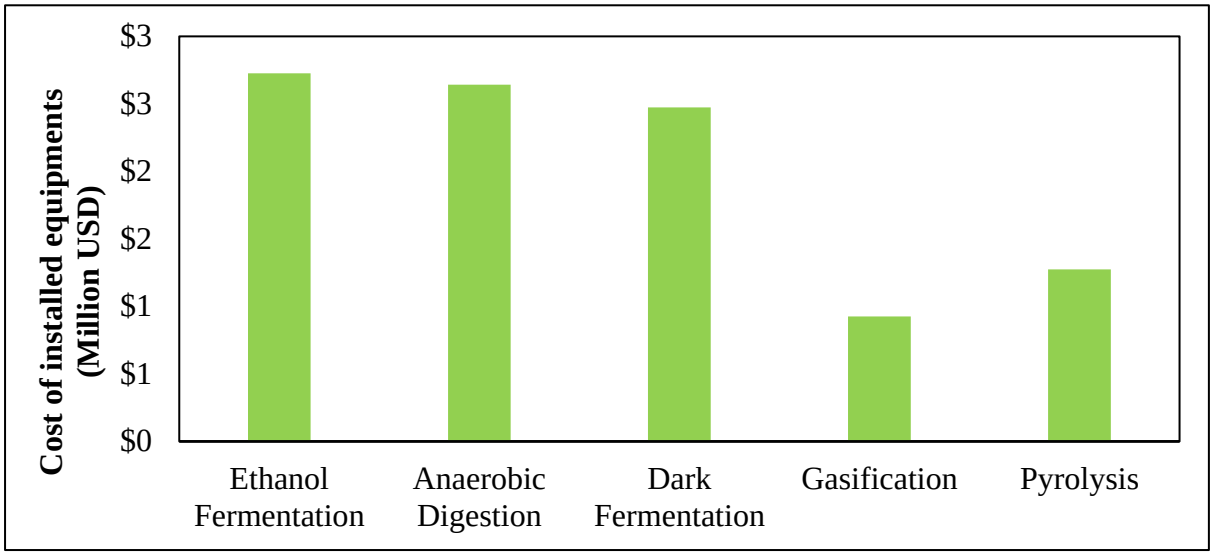

Figure 4-2: Total installed equipment costs for investigated processing routes

4.3.2. CAPEX

The installed equipment cost was used to estimate the fixed capital cost, working capital, and start-up cost for the capital expenditure (CAPEX) estimation. These costs were estimated as described in Section 3.3.1. The CAPEX results are presented in Table 4-12. A summary of the CAPEX for the investigated process routes is depicted in Figure 4-3.

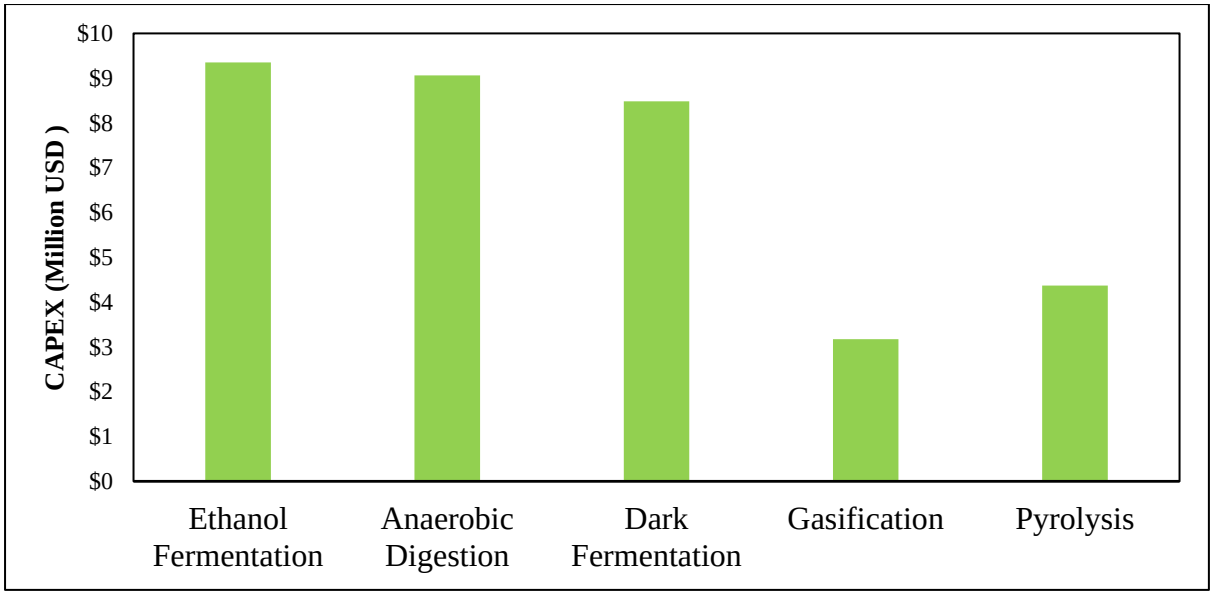

Figure 4-3: CAPEX for investigated processing routes

Table 4-12: CAPEX cost categories for the investigated processes

Cost	Ethanol Fermentation	Anaerobic digestion	Dark Fermentation	Gasification	Pyrolysis
Inside Battery Limits (ISBL) (Million USD)	$2.73	$2.64	$2.47	$0.92	$1.27
Off-Site Battery Limits Investment (OSBL)(Million USD)	$1.09	$1.06	$0.99	$0.37	$0.51
sum of ISBL and OSBL (Million USD)	$3.82	$3.70	$3.46	$1.29	$1.78
Engineering Costs (EC) (Million USD)	$0.38	$0.37	$0.35	$0.13	$0.18
Contingency Costs (CC) (Million USD)	$0.38	$0.37	$0.35	$0.13	$0.18
Fixed Capital Investment (FCI) (Million USD)	$8.40	$8.14	$7.62	$2.85	$3.92
Working Capital (WC) (Million USD)	$0.57	$0.55	$0.52	$0.19	$0.27
Startup Costs (SUC) (Million USD)	$0.38	$0.37	$0.35	$0.13	$0.18
Capital Expenditure (CAPEX) (Million USD)	**$9.35**	**$9.06**	**$8.48**	**$3.17**	**$4.37**

Fermentation has the highest capital expenditure (CAPEX) among all the investigated process routes, with a CAPEX of 9.35 million USD. This reflects the complex infrastructure requirements, particularly for the ethanol purification section. The significant ISBL and OSBL investments contribute to the high upfront capital cost, making fermentation the most capital-intensive process route among the five technologies. Anaerobic digestion follows fermentation in terms of capital investment, with a CAPEX of 9.06 million USD. Dark fermentation has a CAPEX of 8.48 million USD, which is slightly lower than both fermentation and anaerobic digestion. Gasification has the lowest CAPEX of 3.17 million USD. Pyrolysis has the second-lowest CAPEX, following gasification, with a total of 4.37 million USD.

4.3.3. OPEX

Operating expenditure (OPEX) for the investigated process routes included both fixed and variable costs. These costs included raw materials and other process inputs. Sugarcane bagasse was assumed to be obtained at no cost, as the biorefineries were assumed to be annexed to the sugar mill. Raw materials included other inputs, such as microorganisms for enzyme production, which were classified as variable operating expenses. Fixed costs included operating labour, general plant overhead, environmental charges, and property taxes and insurance. Figure 4-4 and Table 4-13 compares the operating expenditure (OPEX) of the five investigated process routes.

Fermentation has the highest OPEX of 52.47 million USD, primarily driven by the extremely high electricity cost of 42.24 million USD. In addition, the raw material cost of 6.05 million USD is relatively high, contributing significantly to the overall variable costs. The reliance on energy-intensive process steps, such as distillation and purification, is the main cause of the elevated electricity costs. Anaerobic digestion has a lower OPEX compared to fermentation, amounting to 28.98 million USD. Similar to fermentation, electricity represents the highest cost component at 24.13 million USD, while raw material costs are notably lower at 1.59 million USD.

Dark fermentation has an OPEX of 26.85 million USD, with both raw material and electricity costs being lower than those of fermentation and anaerobic digestion. The electricity cost for dark fermentation is 19.56 million USD, while raw material expenses amount to 4.20 million USD. The raw material costs in dark fermentation are increased by the solvent required for

acetic acid recovery. Gasification has the second-highest OPEX after fermentation, with an overall cost of 34.29 million USD. This is largely due to its substantial electricity costs of 31.20 million USD. Gasification does not incur raw material costs, as sugarcane bagasse is the only feedstock and is assumed to be freely available as a waste by-product. Steam production was included as part of the energy requirements and was accounted for as electricity in this study. Pyrolysis has the lowest OPEX of 10.56 million USD, with electricity contributing the largest portion at 7.55 million USD. Similar to gasification, pyrolysis does not incur raw material costs.

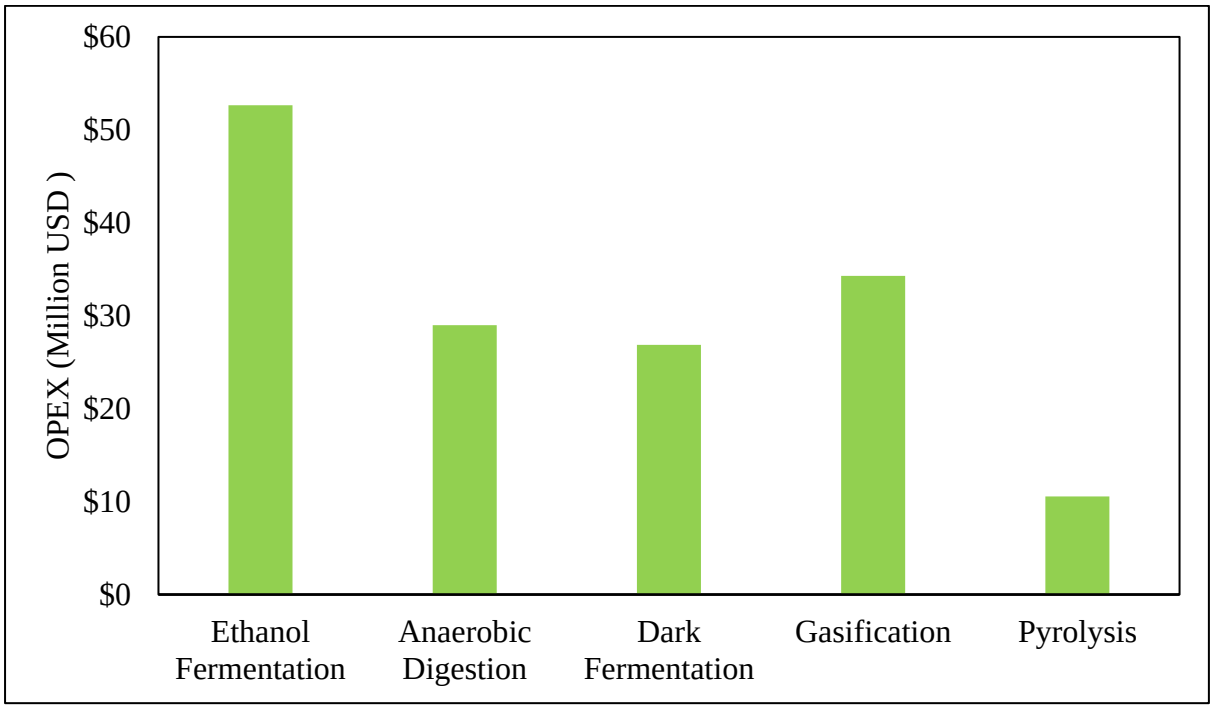

Figure 4-4: OPEX for investigated processing routes

Table 4-13: Operating expenses for the investigated processes

Cost	Ethanol Fermentation	Anaerobic digestion	Dark Fermentation	Gasification	Pyrolysis
Cost of raw materials (Million USD)	$6.05	$1.59	$4.20	$-	$-
Cost of water(Million USD)	$1.22	$0.16	$0.14	$0.14	$0.01
Cost of electricity (Million USD)	$42.24	$24.13	$19.56	$31.20	$7.55
Variable Operating costs (Million USD)	**$49.51**	**$25.88**	**$23.90**	**$31.34**	**$7.57**
Fixed Operating Costs (Million USD)	**$3.14**	**$3.10**	**$2.95**	**$2.96**	**$2.99**
OPEX (Million USD)	**$52.65**	**$28.98**	**$26.85**	**$34.29**	**$10.56**

4.3.4. Total sales

The total sales for the investigated processing routes were determined based on the useful products generated in each process. Digestate was assumed not to be sold; however, it was assumed to be utilised in the sugar mill for steam generation in the existing boilers, since the biorefineries were assumed to be annexed to the sugar mill. Fermentation and anaerobic digestion had one useful product each that was considered for sale. Dark fermentation had two useful products, namely biohydrogen and acetic acid. Gasification had two products considered for sales purposes, which included syngas and biochar. Lastly, pyrolysis had three useful products, namely bio-oil, biochar, and syngas. The study promotes the circular economy concept, and all process streams were assumed to be treated and reused where possible. The estimation of total sales was based on prices obtained from literature, suppliers, and specific market reports and websites. The prices used in estimating total sales are presented in Table 4-14, together with the referenced sources.

Table 4-14: Prices of useful products used to estimate total sales

Product	Price ($/kg)	References
Bioethanol	0.58	TradingEconomics (2024)
Biomethane	1.44	Petersson (2009); IEABioenergyTask37 (2022)
Biohydrogen	2	Hallenbeck and Ghosh (2009); Show, Lee, and Chang (2011); Cleanhydrogenpartnership (2024)
Syngas	0.4	Swanson *et al.* (2010); IEABioenergy (2023)
Biochar	0.16	Lehmann *et al.* (2015); WorldBiocharFoundation (2024)
Bio-oil	0.45	Wright *et al.* (2010); Bridgwater (2012);SAshares.co.za (2024)
Acetic acid	0.36	Straathof (2014); ChemAnalyst (2024)

Table 4-15 presents the annual total sales for each investigated process route. The sales were estimated assuming the plant operates for 5000 hours per year, based on the hourly production rates obtained from the Aspen Plus mass balance simulation results.

Table 4-15: Total sales revenue for the investigated process routes

Processing route	Total revenue(Million USD/year)
Ethanol Fermentation	$30.02
Anaerobic digestion	$36.41
Dark Fermentation	$39.67
Gasification	$38.75
Pyrolysis	$44.89

In terms of sales revenue, pyrolysis shows the highest annual sales revenue among all the investigated process routes, with a total of 44.89 million USD per year. This high revenue is attributed to the production of multiple valuable products, which contribute significantly to overall sales.

Dark fermentation follows, with a total annual sales revenue of 39.67 million USD per year, generated from the sale of biohydrogen and acetic acid. This high sales value is largely driven by acetic acid, which contributes a substantial portion of the revenue due to its higher production yield.

Gasification generates a total sales revenue of 38.75 million USD per year, while anaerobic digestion yields 36.41 million USD per year. The relatively high sales revenue from anaerobic digestion is mainly attributed to the higher biomethane yield, despite its lower unit selling price compared to biohydrogen. Ethanol fermentation has the lowest annual sales revenue of 30.02 million USD per year.

Overall, total sales revenue is strongly influenced by both product yield and unit selling price. Among all the investigated biofuels, biohydrogen has the highest unit selling price; however, its relatively low yield in dark fermentation limits its direct contribution to total route sales. In contrast, acetic acid, which is produced at a significantly higher yield, substantially increases the overall sales revenue for dark fermentation. The comparison of annual total sales revenues for the investigated process routes is presented in Figure 4-5.

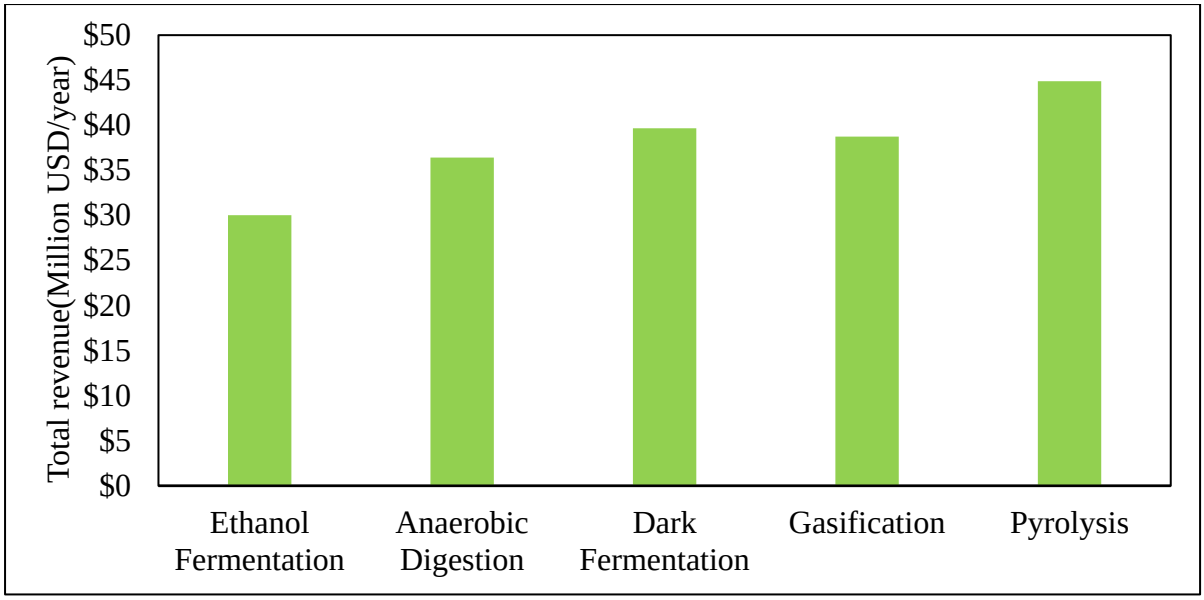

Figure 4-5: Comparison of total annual sales revenue for the investigated process

4.3.5. Gross profit

Gross profit measures the difference between revenue and the cost of goods sold, the operating expenses (OPEX), indicating the efficiency of core production activities. It is a crucial metric for assessing the economic viability of the production processes. Table 4-16 present the gross profit presented by each process route investigated.

Table 4-16: Gross Profit of investigated Process route

Processing route	Gross Profit (Million USD/year)
Ethanol fermentation	-$22.62
Anaerobic digestion	$7.43
Dark Fermentation	$12.82
Gasification	$4.46
Pyrolysis	$34.33

Bioethanol production exhibits a negative gross profit of −22.62 million USD per year, indicating that the process operates at a loss. Despite generating sales revenue, the negative gross profit shows that the operating costs exceed the total revenue, highlighting the economic challenges associated with this process route due to its high operating expenses.

Anaerobic digestion records a positive gross profit of 7.43 million USD per year, indicating that the revenue generated from biomethane sales is sufficient to offset operating costs.

Dark fermentation achieves a gross profit of 12.82 million USD per year, which is primarily driven by the contribution of co-products, particularly acetic acid, in addition to biohydrogen. Pyrolysis yields the highest gross profit of 34.33 million USD per year, which is attributed to its high total sales revenue combined with comparatively lower operating costs. Gasification generates a positive but smaller gross profit of 4.46 million USD per year, reflecting moderate revenues relative to its operating expenses.

The comparison of the annual gross profit of the investigated processes is presented in Figure 4-6.

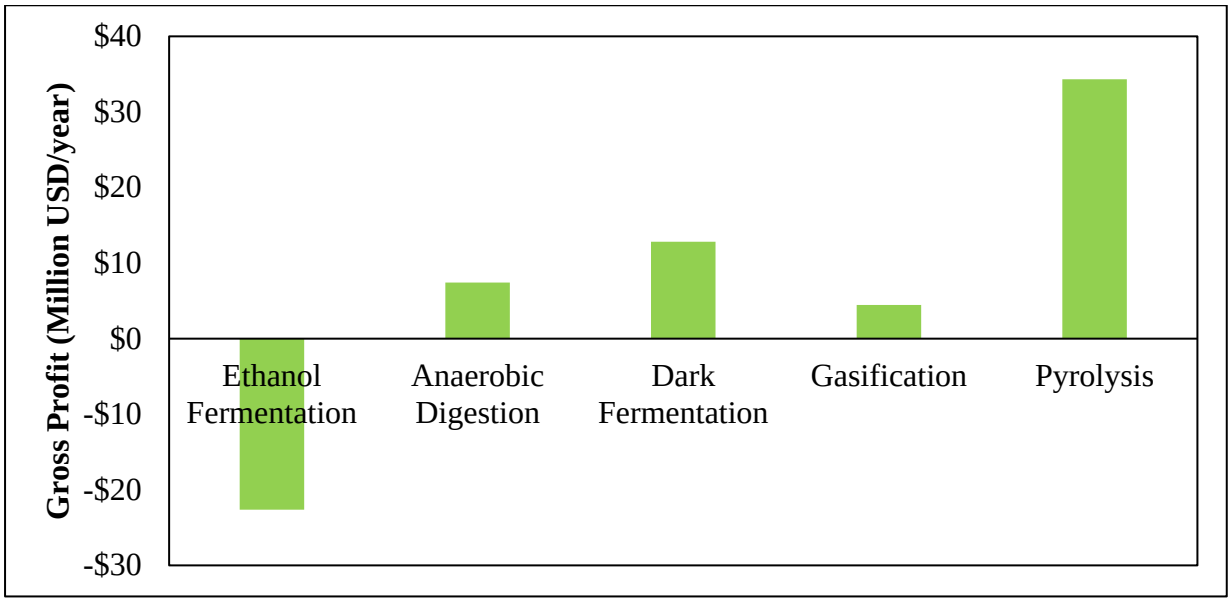

Figure 4-6: Gross Profit of the investigated processes

4.3.6. Economic indicators

Four economic feasibility indicators were used in this study to further assess and compare the economic viability of the investigated processing routes and to identify the most economically feasible option. These indicators include the payback period (PBP), rate of return on investment (ROI), net present value (NPV), and profitability index (PI). Together, these indicators provide a robust framework for evaluating financial performance by considering profitability, risk, and investment efficiency.

Table **4-17** presents the economic indicators for the investigated processing routes, including total sales revenue and gross profit, which were discussed in the previous sections.

Table 4-17: Economic indicators of the investigated processes.

Economic indicator	Bioethanol Fermentation	Anaerobic digestion	Dark Fermentation	Gasification	Pyrolysis
Total Revenue (Million USD/year)	30.02	36.41	39.67	38.75	44.89
Gross Profit (Million USD/year)	-22.62	7.43	12.82	4.46	34.33
Net Present Value (NPV) (Million USD)	-142.23	37.57	67.41	23.21	199.44
Payback Period (years)		4.4	3.3	3.6	1
Rate of Return on Investment (ROI)		1.16	1.51	1.40	10.27
Profitability Index(PI)		5.85	7.95	7.31	46.64

4.3.6.1 Net Present Value (NPV)

Net present value (NPV) represents the difference between the present value of cash inflows and cash outflows over the project lifetime, and therefore reflects the accumulated net cash flow at the end of the project life. NPV was determined using discounted cash flow analysis, and the net cash flow profiles for the investigated process routes are presented in Appendix D. The NPV was calculated as the sum of the discounted cash flows. A positive NPV indicates that the project is expected to generate value beyond its initial investment, making it economically attractive.

Ethanol fermentation exhibits a negative NPV of −142.23 million USD, indicating that the process would result in a net loss over the project lifetime. In contrast, anaerobic digestion records a positive NPV of 37.57 million USD, suggesting that the process is economically feasible under the assumed conditions. Dark fermentation achieves an NPV of 67.41 million USD, indicating strong economic viability and value generation beyond the initial investment. Pyrolysis shows the highest NPV of 199.44 million USD, reflecting the most favourable economic performance among the investigated process routes. Gasification also records a positive NPV of 23.21 million USD, indicating moderate economic performance.

Overall, the positive NPVs obtained for anaerobic digestion, dark fermentation, pyrolysis, and gasification suggest that these process routes are economically feasible under the assumed conditions. The comparison of NPV values for the investigated process routes is presented in Figure 4-7.

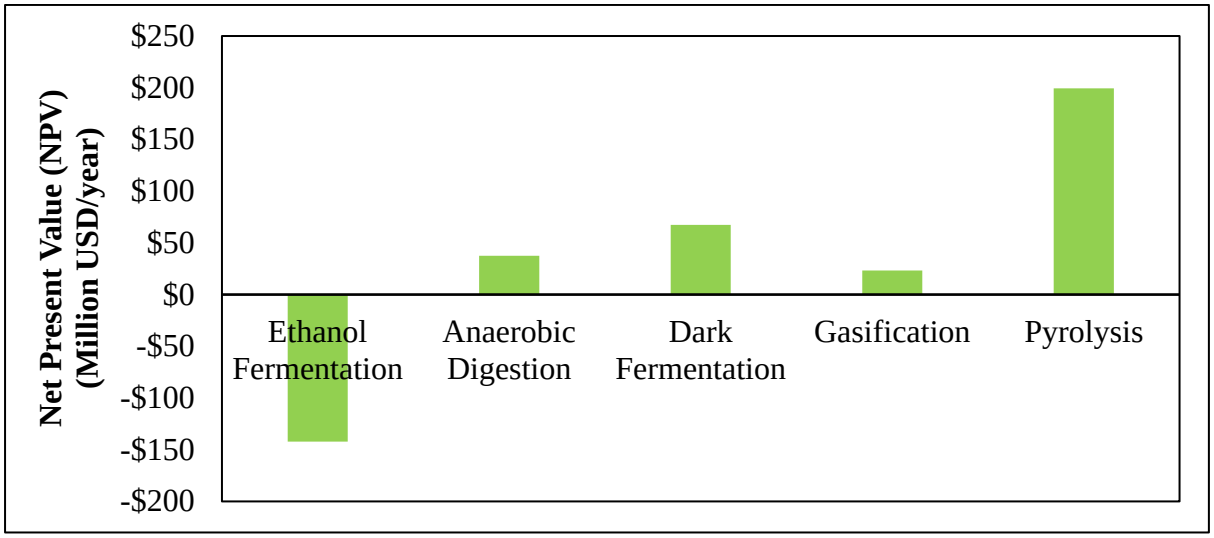

Figure 4-7: Comparison of NPV of the investigated processes

4.3.6.2 Payback Period (PBP)

The payback period (PBP) quantifies the time required to recover the initial investment from net cash flows. It is a key indicator for assessing investment risk and liquidity, where shorter payback periods indicate lower risk and faster capital recovery. The PBP for ethanol fermentation was not calculated due to its negative average annual cash flows.

Among the remaining process routes, dark fermentation has the shortest payback period of 0.8 years, indicating rapid recovery of the initial investment. Pyrolysis follows with a payback period of 1.0 year, while gasification has a payback period of 2.9 years. Anaerobic digestion has the longest payback period of 4.4 years, indicating a slower recovery of the initial investment compared to the other economically feasible process routes. These results suggest that dark fermentation and pyrolysis are associated with lower financial risk, while anaerobic digestion presents a longer investment recovery period. The comparison of PBP values for the investigated process routes is presented in Figure 4-8.

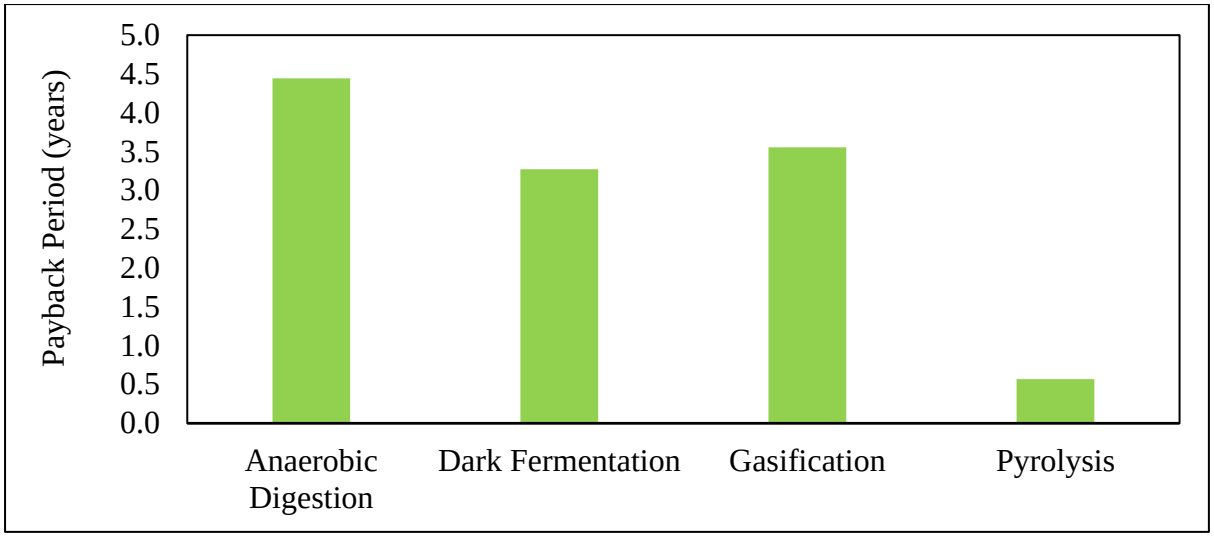

Figure 4-8: The comparison of the PBP of the investigated processes

4.3.6.3 Rate of Return on Investment (ROI):

The rate of return on investment (ROI) measures the efficiency with which invested capital is converted into profit. Higher ROI values indicate more attractive investment opportunities. Pyrolysis exhibits the highest ROI of 10.07, indicating strong profitability relative to its investment cost. Dark fermentation follows with an ROI of 5.39, reflecting efficient capital utilisation. Gasification records an ROI of 1.67, suggesting moderate investment returns. Anaerobic digestion has an ROI of 1.14, indicating lower profitability compared to the other economically feasible process routes. Ethanol fermentation was excluded from ROI analysis due to its negative cash flows. The comparison of ROI values for the investigated process routes is presented in Figure 4-9.

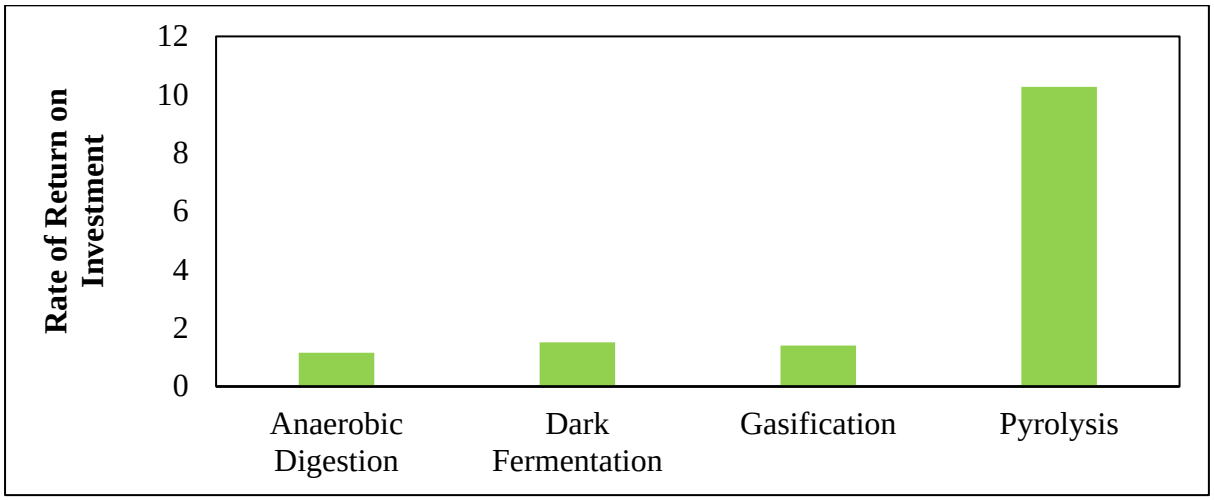

Figure 4-9: Comparison of ROI for the investigated process routes

4.3.6.4 Profitability Index (PI)

The profitability index (PI) is defined as the ratio of the net present value (NPV) to the initial investment and is used to assess project profitability. A PI greater than 1 indicates that the project generates value exceeding its initial investment, while a PI less than 1 indicates an economically unattractive project.

Pyrolysis exhibits the highest PI of 30.93, demonstrating exceptional profitability. Dark fermentation follows with a PI of 8.96, while gasification records a PI of 2.93, indicating that both process routes are economically viable. Anaerobic digestion has a PI of 1.49, suggesting that the process is economically feasible, although less profitable compared to pyrolysis and dark fermentation. Ethanol fermentation exhibits a PI below unity, confirming that the process is not economically profitable under the conditions considered. The comparison of PI values for the investigated process routes is presented in Figure 4-10.

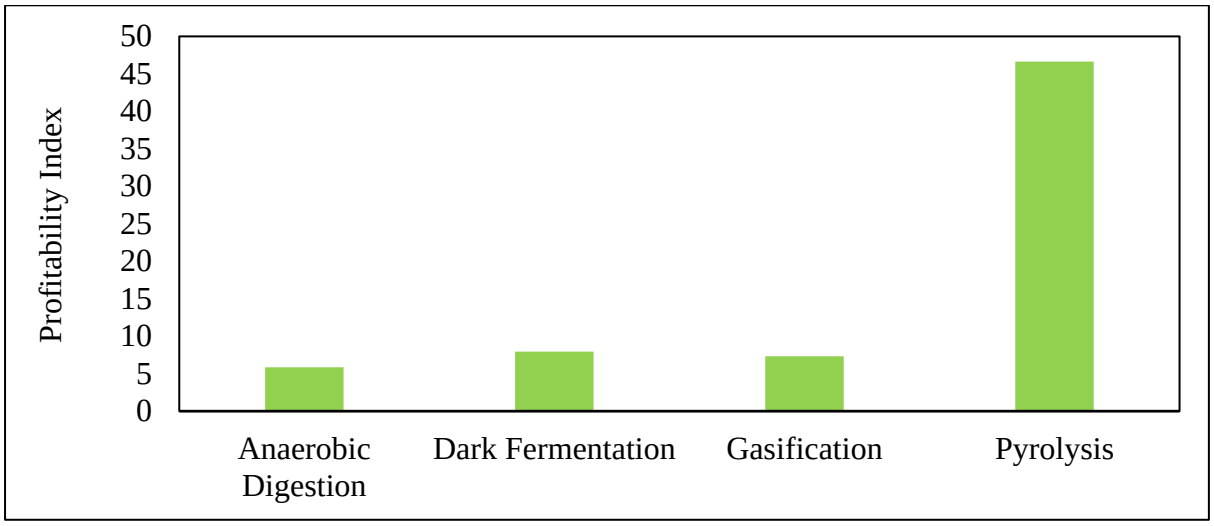

Figure 4-10: Comparison of PI for the investigated process routes

4.3.7. Sensitivity Analysis

Economic risks for a project may arise based on the information used in the techno-economic evaluation. Future variations in TEA information, often in the form of forecasts or estimates, may impact project feasibility. This study conducted a sensitivity analysis by varying each economic parameter within a range of −20 to +20% from their original values for the chosen plant scenario. This analysis shows which economic parameters (selling price, investment capital, and operating costs) have a greater impact on the economic indicators. The selected range of technoeconomic parameters aims to ensure project robustness. This range variation determines which parameters have a greater impact on the economic indicators of the investigated processes (Zepeda *et al.* 2024).

4.3.7.1 CAPEX

A sensitivity analysis was conducted to evaluate the impact of capital expenditure (CAPEX) variations on the economic performance of the five processes investigated: ethanol fermentation, anaerobic digestion (AD), dark fermentation (DF), gasification, and pyrolysis. CAPEX was adjusted by ±20% from the base case to assess its influence on key economic indicators, including net present value (NPV), payback period (PBP), return on investment (ROI), and profitability index (PI). The results indicate that ethanol fermentation remained economically unviable across all CAPEX scenarios, maintaining negative NPV, ROI, and PI values. Increasing CAPEX from the base case of 0% to +20% resulted in a decline in NPV from −142.23 million USD to −144.10 million USD, while ROI improved slightly from −2.42 to −2.02; however, profitability remained negative. AD, DF, gasification, and pyrolysis exhibited greater resilience to CAPEX fluctuations, with only moderate reductions observed in NPV, ROI, and PI as CAPEX increased. AD showed a decrease in NPV from 37.57 million USD to 36.29 million USD and a reduction in PI from 5.85 to 4.71 as CAPEX increased by 20%, while its payback period increased from 4.40 to 5.52 years. DF remained consistently profitable, maintaining a positive NPV and ROI across all CAPEX ranges, although its profitability declined slightly as CAPEX increased. Gasification also sustained positive economic performance across the evaluated scenarios. Pyrolysis demonstrated the strongest economic performance overall, achieving the highest NPV and PI values across all CAPEX changes, although both indicators decreased with increasing CAPEX. Overall, the findings confirm that CAPEX is an important determinant of economic viability, with processes such

as pyrolysis and DF showing greater economic robustness compared to ethanol fermentation. Figure 4-11 illustrates the sensitivity of the economic indicators to CAPEX.

4.3.7.2 OPEX

A sensitivity analysis was conducted to evaluate the impact of operating expenditure (OPEX) variations on the economic performance of the five processes examined: bioethanol fermentation, anaerobic digestion (AD), dark fermentation (DF), gasification, and pyrolysis. OPEX was adjusted by ±20% from the base case to assess its influence on key economic indicators, including NPV, payback period (PBP), ROI, and profitability index (PI). The results indicate that bioethanol fermentation remained economically unviable across all scenarios, with consistently negative NPV, ROI, and PI values. Increasing OPEX by 20% caused the NPV to decrease from −142.23 million USD to −204.07 million USD, while ROI declined from −2.42 to −3.55, demonstrating strong sensitivity to rising operating costs. AD and DF showed moderate sensitivity, with both processes experiencing declining profitability as OPEX increased. AD exhibited a decrease in NPV from 37.57 million USD to 3.25 million USD and a reduction in PI from 5.85 to 0.51 at +20% OPEX, accompanied by a substantial increase in payback period from 4.40 to 51.38 years, indicating reduced economic viability under high operating costs. DF remained comparatively more resilient, maintaining positive NPV and PI values across all scenarios, although its profitability declined from 67.41 million USD to 35.61 million USD as OPEX increased by 20%. Gasification showed high sensitivity to OPEX, with NPV decreasing from 23.21 million USD to −17.40 million USD and PI declining from 7.31 to −5.48 at +20% OPEX, indicating that the process becomes economically unfeasible under increased operating costs. Pyrolysis demonstrated the strongest economic performance overall, maintaining the highest NPV and PI values across all scenarios, despite gradual reductions as OPEX increased. Overall, the findings confirm that OPEX is a critical determinant of economic viability, particularly affecting processes with higher operating cost requirements. Figure 4-12 illustrates the sensitivity of economic indicators to OPEX.

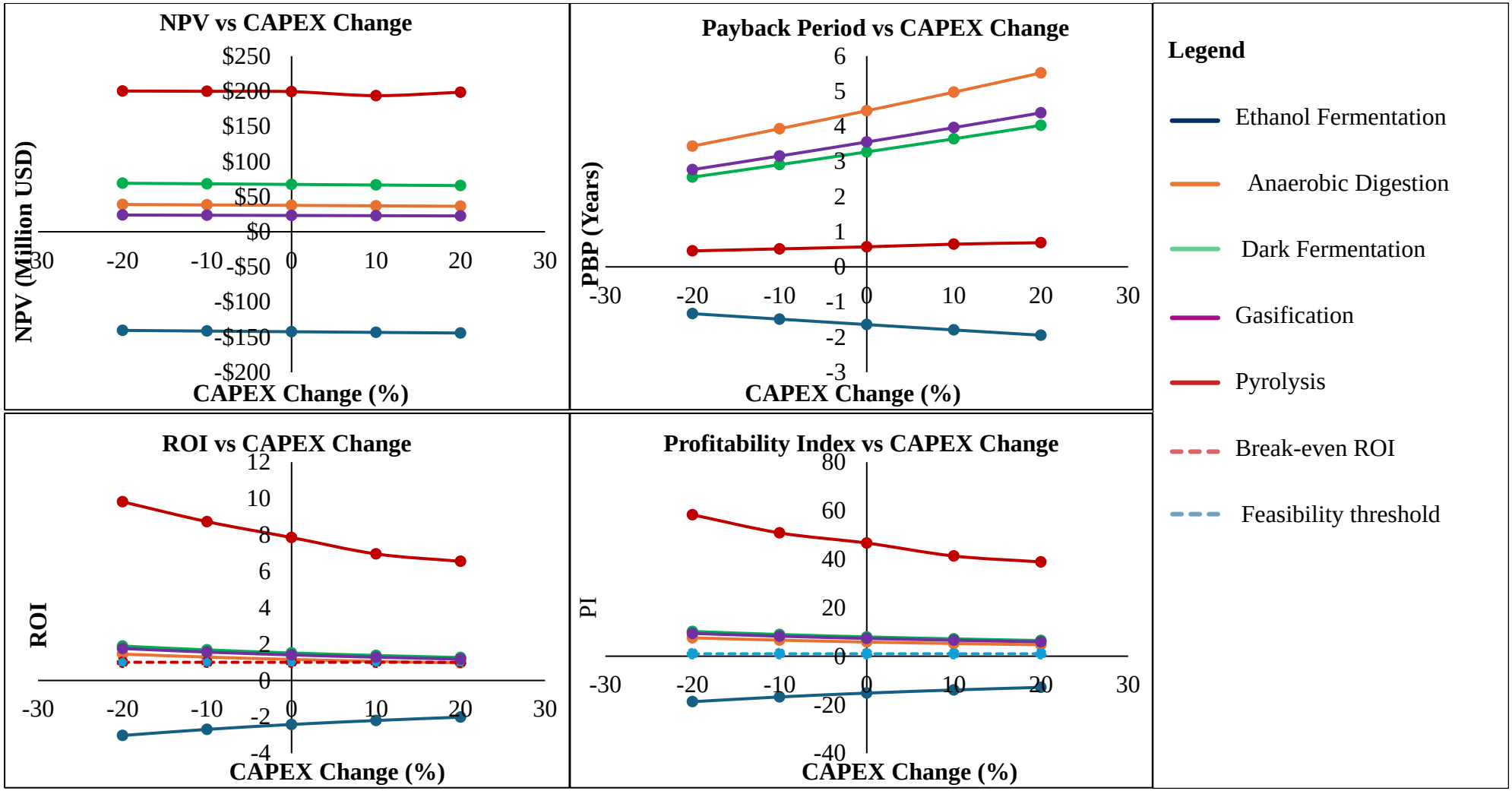

Figure 4-11: Sensitivity of economic indicators to CAPEX

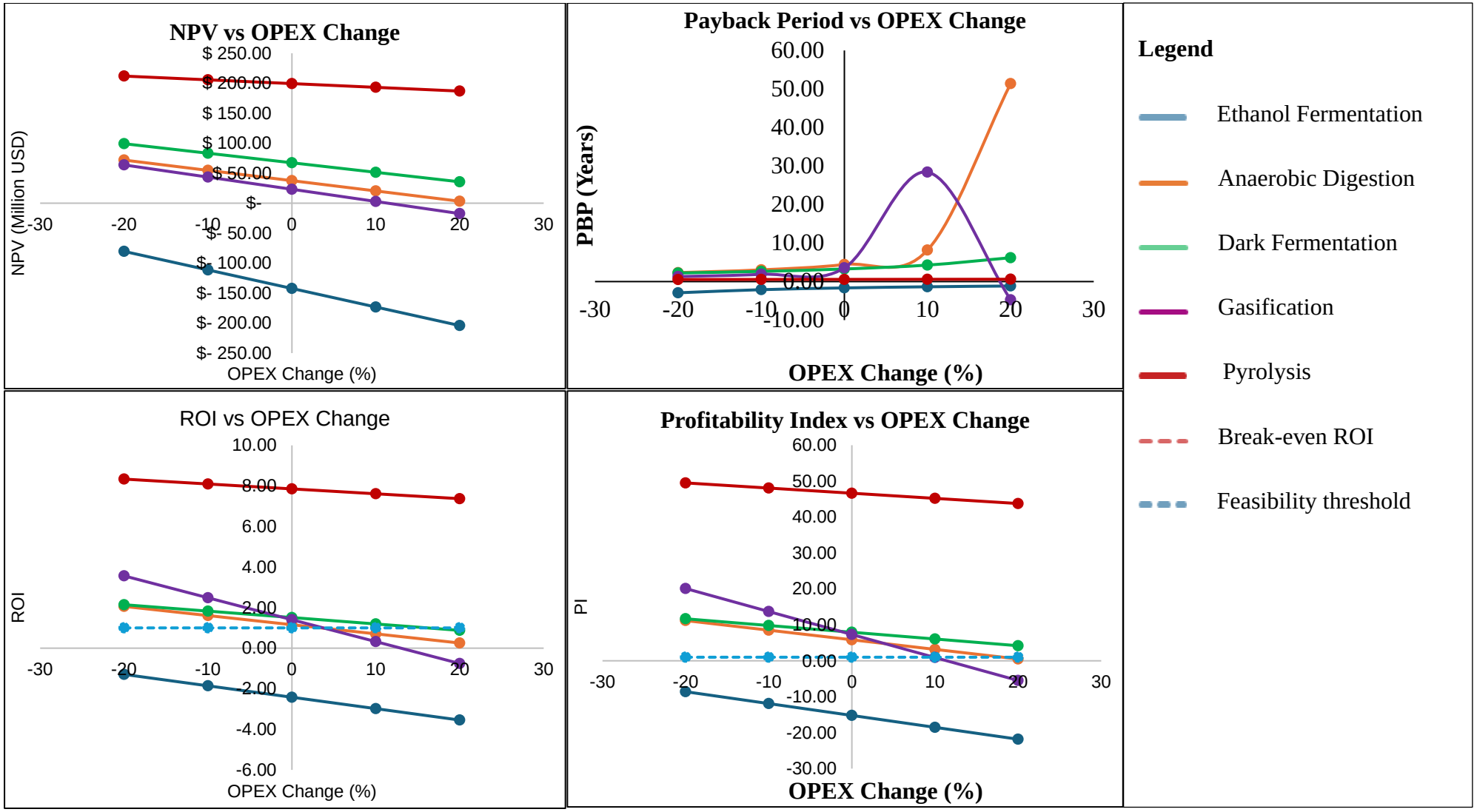

Figure 4-12: Sensitivity of economic indicators to OPEX

4.3.7.3 Selling price

The sensitivity analysis of economic indicators to selling price demonstrated that the five processes exhibited distinct responses to fluctuations in market price, with pyrolysis consistently yielding the most favourable economic performance across all scenarios. Bioethanol production remained economically unviable throughout the assessed range, maintaining negative NPV, ROI, and PI values, although its profitability improved slightly with increasing selling price. At a 20% increase in selling price, the NPV improved from −142.23 million USD to −106.96 million USD; however, the process remained economically infeasible. AD exhibited moderate sensitivity, transitioning from a negative NPV of −5.55 million USD at a 20% price decrease to a positive NPV of 80.69 million USD at a 20% price increase, with ROI increasing from 0.02 to 2.29 and PI improving from 0.86 to 12.57. DF demonstrated strong profitability across all indicators, achieving the highest NPV of 114.38 million USD, an ROI of 2.45, and a PI of 13.48 at a 20% selling price increase, while also reducing its payback period from 3.30 to 1.93 years. Gasification showed substantial sensitivity to selling price, shifting from a negative NPV of −22.68 million USD at −20% to a positive NPV of 69.09 million USD at +20%, with corresponding improvements in ROI and PI. Pyrolysis remained the most economically robust process, attaining the highest NPV and PI values across all price scenarios, with NPV increasing from 146.14 million USD at −20% to 252.75 million USD at +20%. Overall, the findings confirm that selling price is a critical determinant of economic viability, particularly benefiting processes characterised by higher-value products and stronger baseline profitability, such as pyrolysis and DF. Figure 11 illustrates the sensitivity of the economic indicators to the selling price.

4.3.7.4 Discount rate

A sensitivity analysis was conducted to evaluate the impact of discount rate variations on the economic performance of the five processes examined: bioethanol production, anaerobic digestion (AD), dark fermentation (DF), gasification, and pyrolysis. The discount rate was adjusted by ±20% from the base case to assess its influence on key economic indicators, including net present value (NPV), payback period (PBP), return on investment (ROI), and profitability index (PI). The results indicate that bioethanol production remained economically unviable across all scenarios, maintaining negative NPV and PI values, although a reduction in the discount rate slightly improved its NPV from −142.23 million USD to −166.34 million

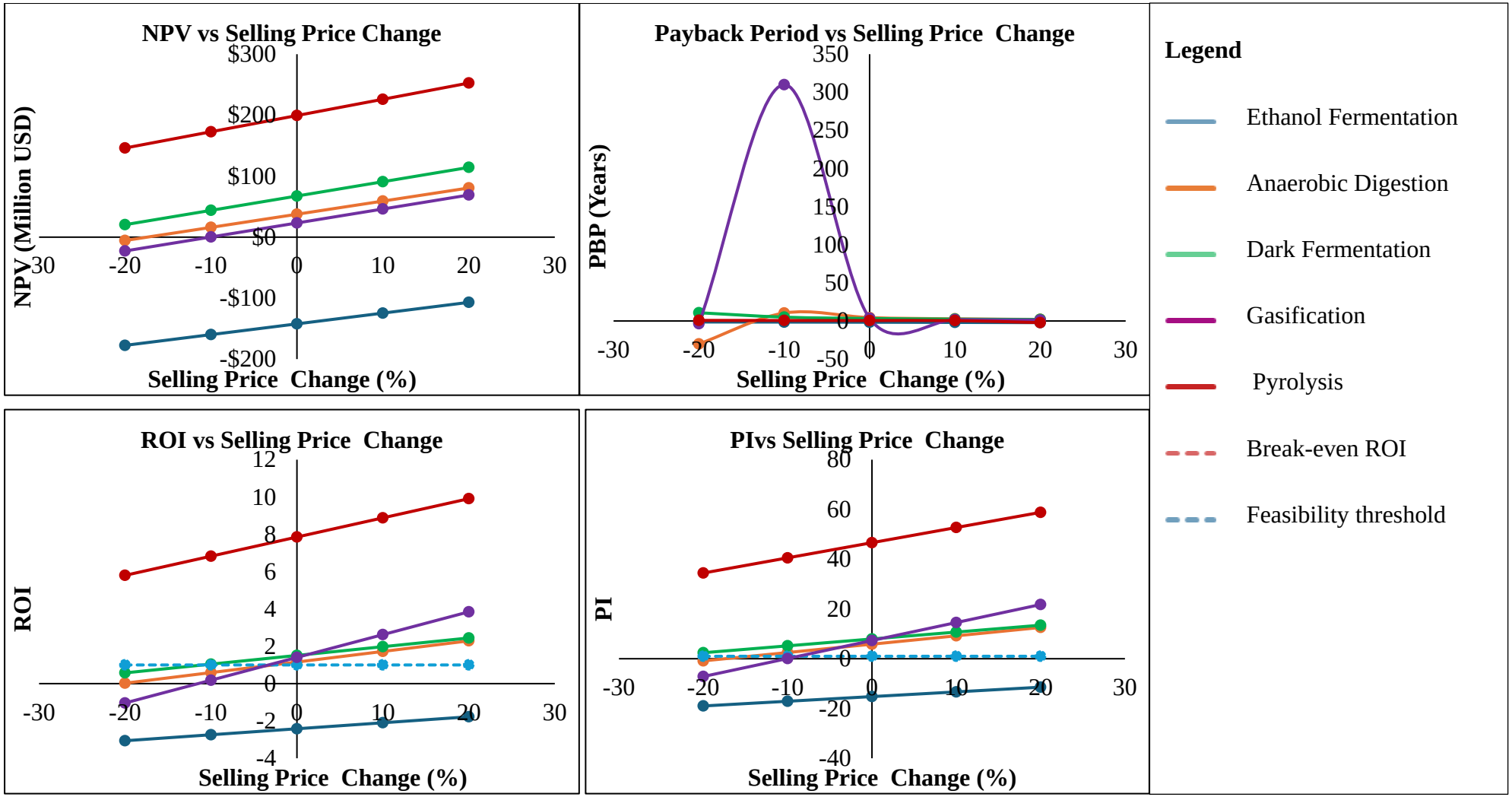

Figure 4-13: Sensitivity of economic indicators to selling Price

USD at −20%, while an increase in the discount rate improved NPV to −123.84 million USD at +20%; however, profitability remained negative throughout. AD, DF, gasification, and pyrolysis demonstrated relatively low sensitivity to discount rate variations compared to other parameters, with gradual decreases in NPV and PI as the discount rate increased. AD showed a decline in NPV from 45.73 million USD at −20% to 31.39 million USD at +20%, with PI decreasing from 7.12 to 4.89 and payback period increasing from 3.70 to 5.32 years. Similarly, DF exhibited a decrease in NPV from 81.48 million USD to 56.75 million USD and a reduction in PI from 9.60 to 6.69 as the discount rate increased, while its payback period rose from 2.70 to 3.89 years. Gasification displayed a comparable trend, with NPV decreasing from 28.10 million USD to 19.50 million USD and PI declining from 8.86 to 6.15 across the evaluated range. Pyrolysis remained the most economically robust process, maintaining the highest NPV and PI values across all discount rate scenarios, although its NPV decreased from 237.28 million USD at −20% to 170.78 million USD at +20%, and PI declined from 55.30 to 40.08. ROI values remained constant across all discount rate scenarios for all processes, indicating that ROI was not influenced by changes in discount rate in this assessment. Overall, the findings confirm that the discount rate affects the economic indicators primarily through reductions in NPV and PI, while pyrolysis and DF remain the most economically viable and resilient processes. Figure 4-14 illustrates the sensitivity of the economic indicators to the discount rate.

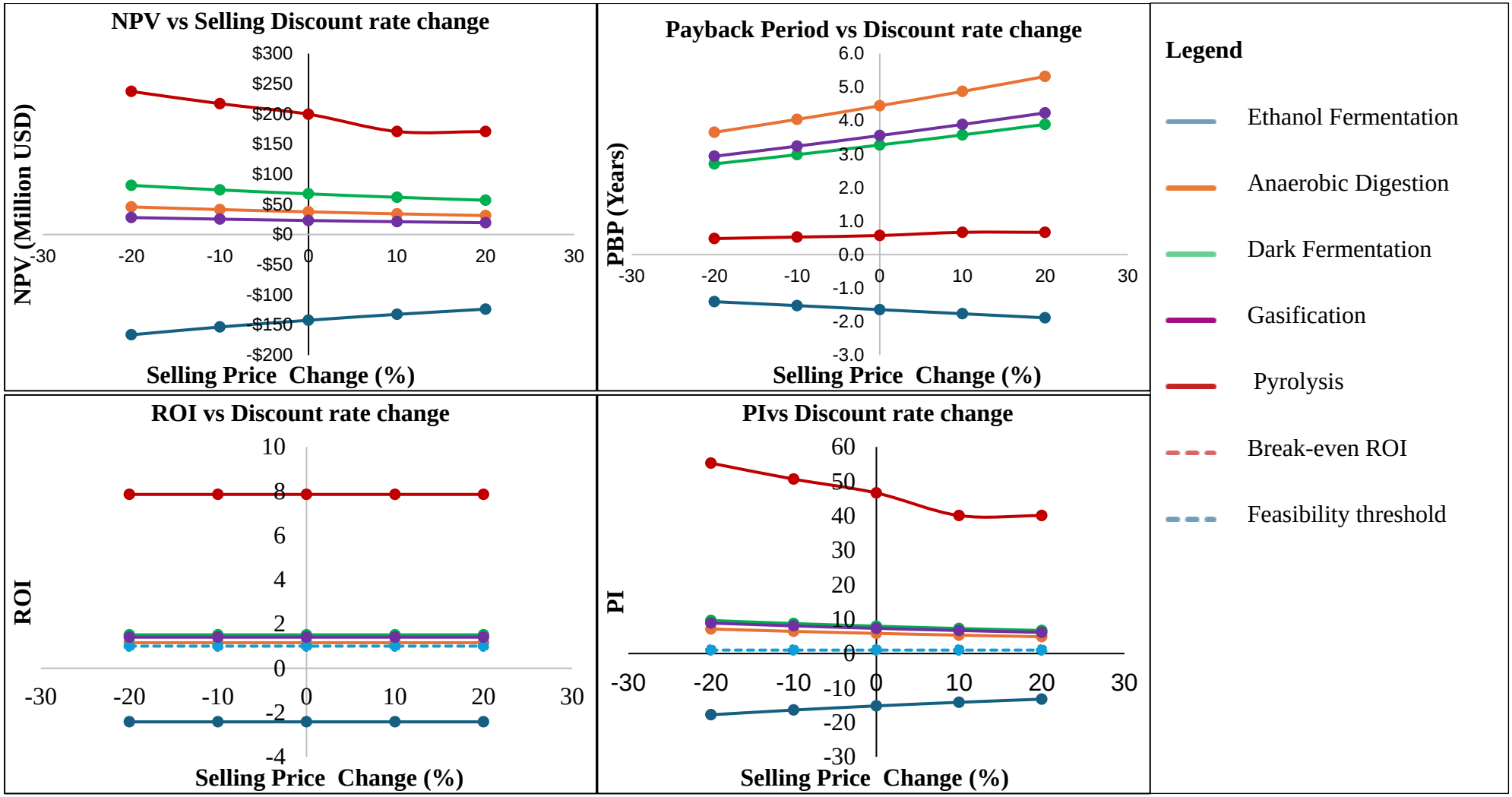

Figure 4-14: Sensitivity of economic indicators to discount rate

4.3.8. Literature comparison and interpretation of economic indicators

Techno-economic evaluation of lignocellulosic biomass conversion pathways commonly relies on complementary indicators such as net present value (NPV), payback period (PBP), return on investment (ROI), and profitability index (PI) to quantify overall feasibility, capital recovery dynamics, and investment attractiveness. Recent reviews of lignocellulosic biorefinery TEA emphasise that these indicators are particularly useful when processes differ in product value, capital intensity, and operating cost structure, and when uncertainty is explored through sensitivity analysis (Swanson *et al.* 2010; Humbird *et al.* 2011; Patel *et al.* 2025).

The base-case results demonstrate clear differences in economic performance among the assessed processes. Pyrolysis achieved the highest total revenue (44.89 million USD per year) and gross profit (34.33 million USD per year), and it exhibited the most favourable investment indicators, including an NPV of 199.44 million USD, an ROI of 7.85, a PI of 46.64, and a payback period of only 1 year. This strong performance is consistent with recent techno-economic studies, which report that thermochemical pathways, particularly pyrolysis, often outperform biochemical routes due to higher-value product streams and the potential for co-product recovery such as biochar and bio-oil. These co-products can significantly enhance profitability and reduce financial risk by diversifying revenue streams (Makepa *et al.* 2023). Furthermore, recent work focusing on sugarcane bagasse pyrolysis has similarly demonstrated that pyrolysis-derived products can offer strong economic returns when product markets are favourable and operating costs are effectively controlled (Wright *et al.* 2010; Bridgwater 2012; Mari Selvam *et al.* 2025).

Dark fermentation and anaerobic digestion also exhibited economic viability under base-case conditions. Dark fermentation achieved a higher NPV (67.41 million USD) and PI (7.95) compared to anaerobic digestion (NPV of 37.57 million USD and PI of 5.85), indicating a stronger economic return relative to investment. These results align with literature demonstrating that anaerobic digestion is frequently feasible when applied to lignocellulosic biomass residues, although profitability remains highly dependent on operating efficiency, energy prices, and upgrading requirements (Show, Lee, and Chang 2011). Similarly, fermentative hydrogen production through dark fermentation is economically favourable under optimised operating conditions, particularly when hydrogen yields are improved and downstream integration is implemented to enhance overall energy recovery (Lantz *et al.* 2007;

Boshagh, van Niel and Lee 2025). Chowdhury (2021) reported a payback period of 5.4 years for anaerobic digestion, which is comparable to the base-case value obtained in this study.

Gasification demonstrated moderate economic performance, achieving positive gross profit (4.46 million USD per year) and a positive NPV of 23.21 million USD, with a payback period of 3.6 years and an ROI of 1.40. Although economically feasible, its profitability was lower than that of pyrolysis and dark fermentation. This is consistent with recent studies indicating that gasification performance is strongly influenced by process scale, syngas cleaning requirements, and downstream utilisation strategies, which can increase costs and reduce net profitability (Kansha, Abbas and Manaf 2024).

In contrast, bioethanol fermentation remained economically unviable in the base case, producing negative gross profit (−22.62 million USD per year), negative NPV (−142.23 million USD), and negative PI (−15.21). This outcome is consistent with recent lignocellulosic ethanol techno-economic assessments, which continue to highlight that second-generation ethanol is constrained by high pretreatment costs, enzyme requirements, and energy-intensive downstream separation processes. These challenges often limit profitability unless significant process optimisation or cost reduction strategies are implemented (Raj *et al.* 2022).

Overall, the base-case ranking observed in this study (pyrolysis > dark fermentation > anaerobic digestion > gasification > bioethanol fermentation) is consistent with recent peer-reviewed TEA literature on lignocellulosic biomass conversion. Thermochemical conversion routes, particularly pyrolysis, tend to demonstrate stronger economic performance due to favourable product values and co-product revenue potential, while biochemical conversion pathways such as lignocellulosic ethanol remain economically constrained under high capital and operating cost assumptions (Patel *et al.* 2025). These findings confirm that process selection for sugarcane bagasse conversion should prioritise pathways that offer higher-value products, strong gross profit margins, and improved financial robustness under uncertain market conditions.

4.4. Life cycle assessment

Life cycle assessment (LCA) is the last and critical component in the evaluation of any production process, particularly in the context of bioenergy and renewable resources. It involves the systematic analysis of the environmental impacts related to a process. By comparing environmental impacts, stakeholders can make informed decisions regarding the adoption and investment in sustainable and environmentally friendly energy technologies. This is important in order to avoid fines, which can affect the cash flow of the business even if the technology is profitable. The LCA for the five investigated processes was performed with the aim of determining the least environmentally friendly processing route. Information regarding the SimaPro simulation is presented in Appendix E, including the database used, as well as process inputs and outputs.

All by-products and co-products from the investigated processes were simulated as avoided products. Carbon dioxide is assumed to be sold to concrete manufacturers. Calcium carbonate, a nano-sized mineral that embeds itself in concrete, can be produced by reacting CO_2 with calcium ions in cement. This reaction reinforces concrete. Instead of steam curing, which is more energy-intensive, concrete mixes can also be cured using CO_2. The digestate is assumed to be used in the sugar mill steam boiler. Water will be stored and used for cooling purposes. Energy requirements for the investigated processes were simulated using electricity, where medium voltage was utilised.

4.4.1. Damage assessment

Table 4-18 below presents the damage assessment results of the LCA study conducted using SimaPro software. The results were obtained using the ReCiPe 2016 Endpoint (H) method, which allows for the assessment of environmental damage impacts. Biohydrogen production consistently shows environmental savings, which can be attributed to the large quantity of avoided product, namely acetic acid.

Table 4-18: Impact assessment damage results for the production of biofuels using a unit mass of 51840 kg of sugarcane bagasse

Damage category	Unit	Ethanol Fermentation	Anaerobic Digestion	Dark Fermentation	Gasification	Pyrolysis
Human health	DALY	0.751	0.249	0.044	0.3	0.074
Ecosystems	species.yr	0.0008	0.0003	0	0.0005	0.0001
Resources	USD2013	5362	2826	-4334	4215	523

Human Health

Figure 4-15 below presents a comparison of the investigated process routes in terms of human health impact. Human health is expressed in Disability-Adjusted Life Years (DALY), which is a measure that reflects the total burden of disease on human beings. The results indicate that the bioethanol fermentation process has the highest human health impact among the investigated processes, followed by gasification, anaerobic digestion, and pyrolysis. The dark fermentation process exhibits the lowest human health impact among the investigated process routes.

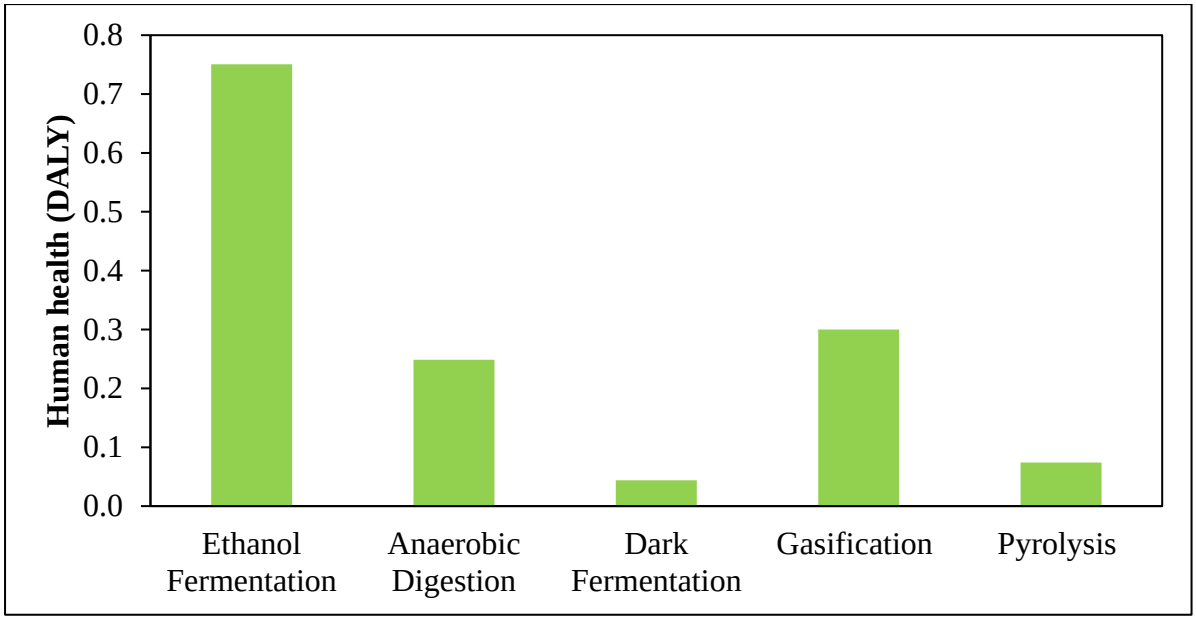

Figure 4-15: Human health impact for investigated processes

Ecosystems

Figure 4-16 presents a comparison of the investigated process routes in terms of ecosystem impact. Ecosystem impact is expressed in units of species per year (species·yr), which

measures the potential loss of species over one year. Overall, the results indicate that all investigated processes have little to no impact on species population decline. However, the bioethanol fermentation process shows the highest ecosystem impact among the evaluated routes, followed by gasification, anaerobic digestion, and pyrolysis, while the dark fermentation process exhibits the lowest ecosystem impact.

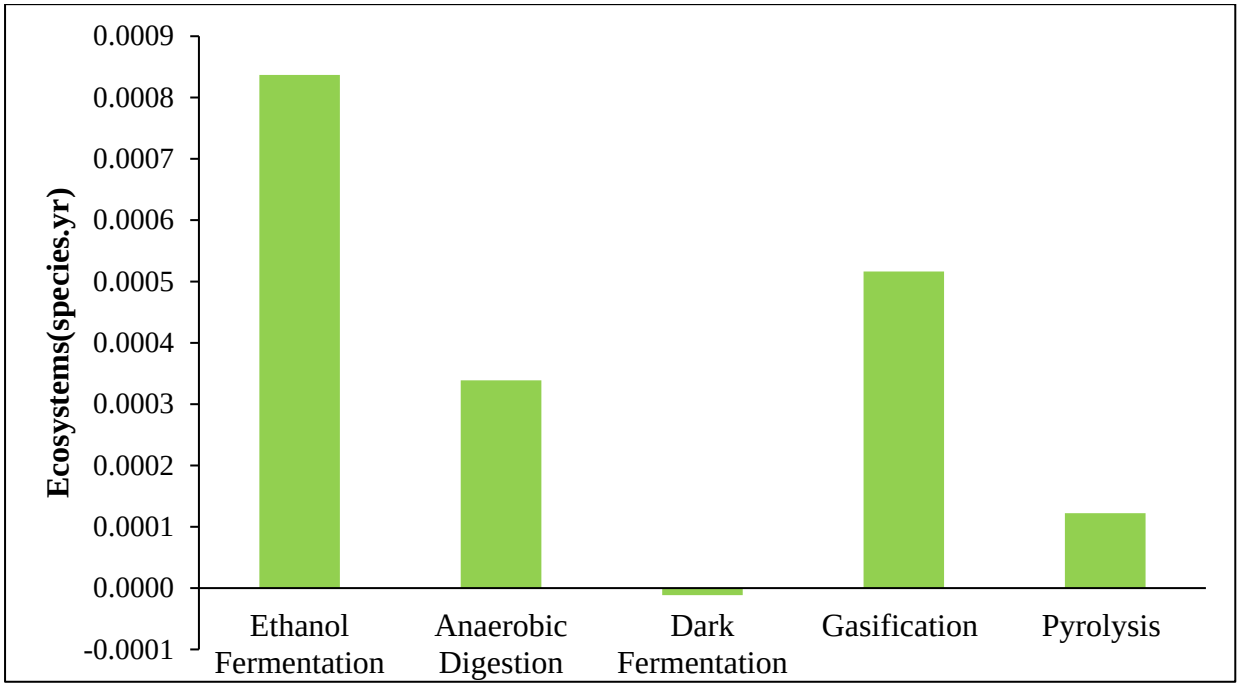

Figure 4-16: Ecosystem impact for investigated processes

Resources

Figure 4-17 presents a comparison of the investigated process routes in terms of resource impact. Resource impact is expressed in economic value (USD2013), which represents the cost associated with resource depletion. The results indicate that the ethanol fermentation process exhibits the highest resource impact among the investigated processes, followed by gasification, anaerobic digestion, and pyrolysis. In contrast, the dark fermentation process shows negative resource impact values, indicating the greatest environmental savings in the resources category due to avoided product credits.

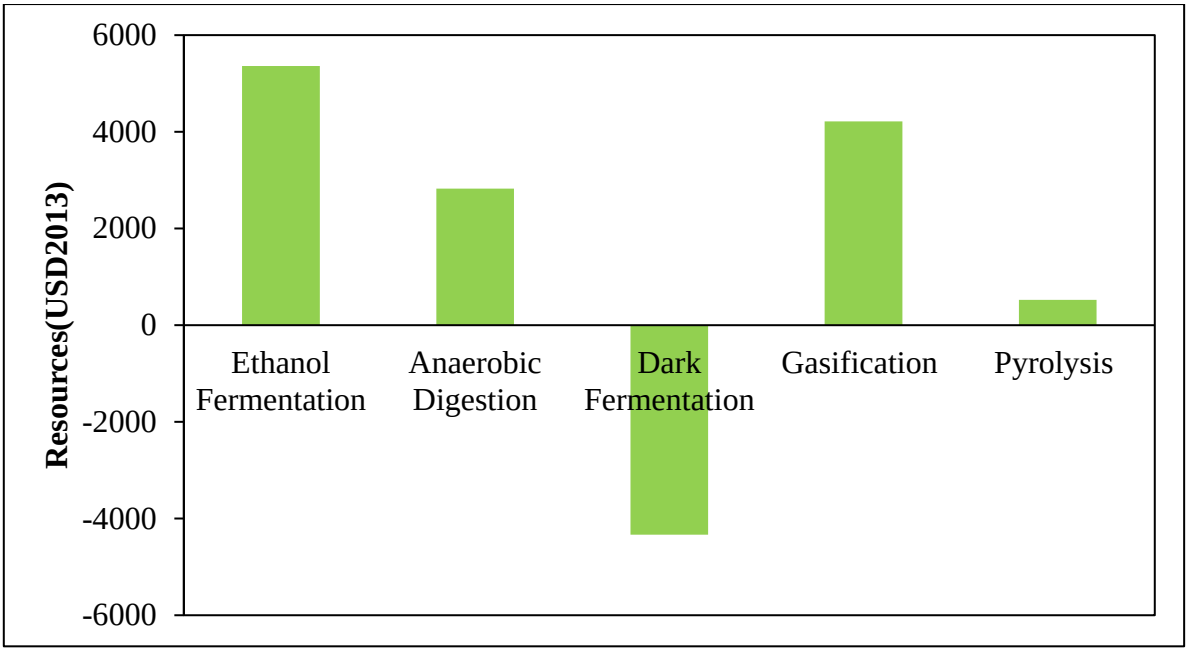

Figure 4-17: Resource impact for investigated processes

4.4.2. Characterisation assessment

Table 4-19 below presents the impact assessment characterisation results of the LCA study conducted using SimaPro software. The results were obtained using the ReCiPe 2016 Midpoint (H) method, which allows for the assessment of individual impact categories. In this study, eight impact categories were evaluated.

Global warming

Global warming refers to the cumulative increase in the Earth's surface temperature observed since the pre-industrial period (between 1850 and 1900). This warming is primarily driven by human activities, particularly the combustion of fossil fuels, which increases the concentration of heat-trapping greenhouse gases in the Earth's atmosphere. Global warming is expressed in terms of carbon dioxide equivalents (CO_2-eq) and represents the contribution of the investigated process routes to climate change. Figure 4-18 presents the global warming results obtained from the SimaPro simulation.

Table 4-19: Impact assessment characterisation results for the production of biofuels using unit mass of 51840 kg sugarcane bagasse

Impact category	Unit	Ethanol Fermentation	Anaerobic digestion	Dark Fermentation	Gasification	Pyrolysis
Global warming	kg CO_2 eq	192882.18	71759.27	-4858.72	91266.99	19135.33
Fine particulate matter formation	kg $PM_{2.5}$ eq	566.60	179.21	54.65	211.26	54.60
Terrestrial acidification	kg SO_2 eq	1942.88	593.87	315.56	687.92	181.47
Freshwater eutrophication	kg P eq	238.41	71.63	30.50	83.12	22.82
Marine eutrophication	kg N eq	7.57	2.52	0.49	3.20	0.84
Mineral resource scarcity	kg Cu eq	-38.16	-32.59	-151.84	31.95	6.17
Fossil resource scarcity	kg oil eq	59834.55	18358.52	-9366.12	26755.54	5627.53
Water consumption	m^3	642.20	115.40	-614.74	238.64	62.57

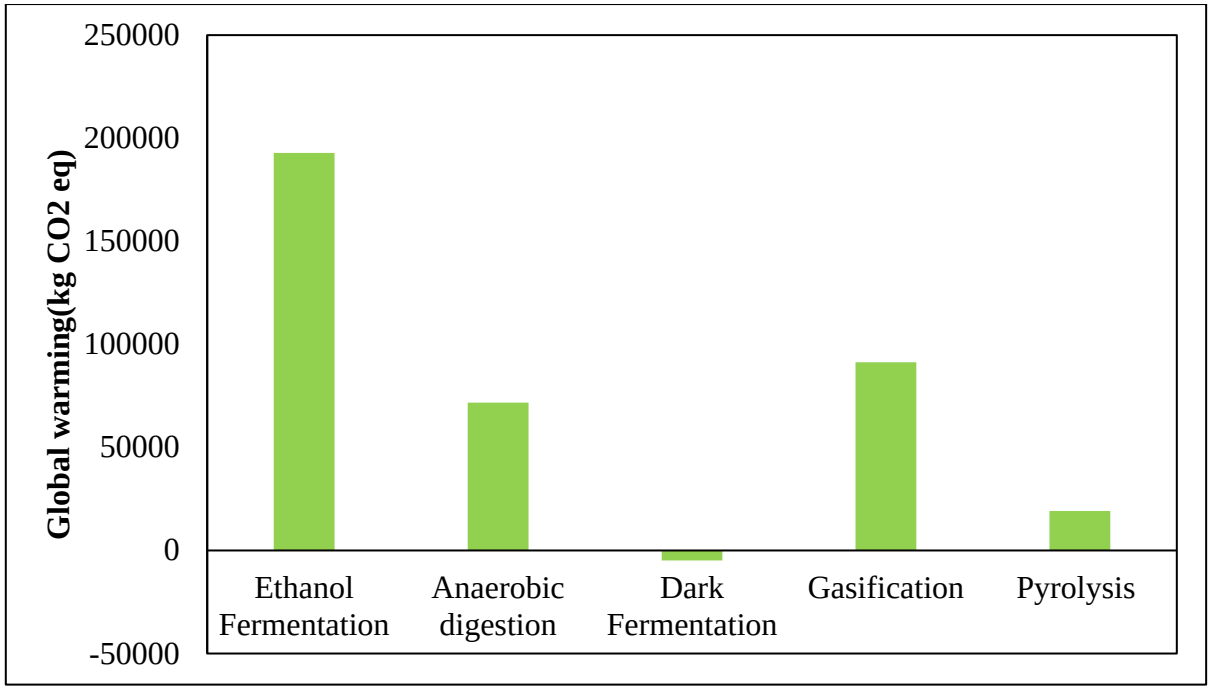

Figure 4-18: Global warming impacts of the investigated process routes

The bioethanol fermentation process shows the highest global warming impact among the evaluated processes, with a value of 192882.18 kg CO_2 equivalent. This is mainly due to the energy-intensive nature of bioethanol production, particularly during the pre-treatment and purification stages. Energy requirements were simulated using electricity, which is currently largely generated from coal combustion, thereby contributing significantly to global warming impacts.

The gasification process also shows a relatively high global warming impact (91266.99 kg CO_2 equivalent), although it is lower than that of the bioethanol fermentation process. Similar to ethanol fermentation, gasification is energy-intensive, as it requires biomass heating to approximately 800 °C. Electricity was assumed as the energy source across all simulated processes. It is therefore observed that processes which consume large amounts of energy tend to exhibit higher contributions to global warming.

The anaerobic digestion process shows a lower global warming impact (71759.27 kg CO_2 equivalent) compared to bioethanol fermentation and gasification, due to its lower energy requirements. The pyrolysis process exhibits a global warming impact of 19135.33 kg CO_2 equivalent.

The dark fermentation process shows the lowest global warming impact (−4858.72 kg CO_2 equivalent). This is attributed to its relatively lower energy requirements compared to bioethanol fermentation, gasification, and anaerobic digestion, as well as the environmental savings associated with avoided acetic acid production.

Fine particulate matter formation

Fine particulate matter consists of tiny particles in the air that are harmful to both the environment and human health. In humans, fine particulate matter can enter the respiratory system and cause serious health problems. Fine particulate matter formation is measured in kilograms of $PM_{2.5}$ equivalent (kg $PM_{2.5}$-eq), which represents the formation of particulate matter with a diameter of 2.5 microns. The impact assessment results for fine particulate matter emissions and formation from the investigated process routes are presented in Figure 4-19.

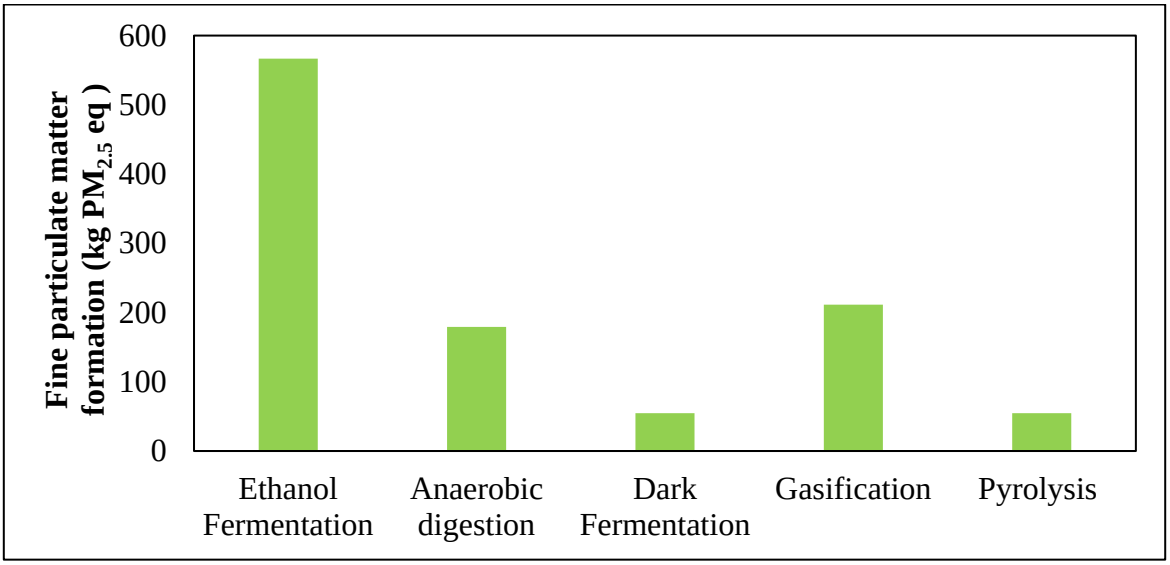

Figure 4-19: Fine particulate matter formation impacts of the investigated process

The dark fermentation process and pyrolysis process show the lowest fine particulate matter formation impacts, with values of 54.65 kg $PM_{2.5}$ eq and 54.60 kg $PM_{2.5}$ eq, respectively. This is followed by the anaerobic digestion process and the gasification process, which exhibit fine particulate matter formation impacts of 179.21 kg $PM_{2.5}$ eq and 211.26 kg $PM_{2.5}$ eq, respectively. The bioethanol fermentation process shows the highest fine particulate matter formation impact, with a value of 566.60 kg $PM_{2.5}$ eq. Figure 4-19 illustrates that the bioethanol fermentation process exhibits the highest fine particulate matter formation among the investigated routes, while the dark fermentation and pyrolysis processes demonstrate the lowest

impacts. The higher particulate matter impact associated with the bioethanol fermentation process is likely attributed to upstream utility and energy requirements, rather than the biological conversion step itself.

Terrestrial acidification

Terrestrial acidification refers to the process whereby land ecosystems and soil become excessively acidic due to the deposition of acidic compounds from the atmosphere. This phenomenon largely results from emissions of nitrogen oxides and sulphur dioxide. Terrestrial acidification contributes to air pollution and may also influence climate change. It is measured in kilograms of sulphur dioxide equivalent (kg SO_2 eq). Figure 4-20 present the terrestrial acidification impacts for the investigated process routes.

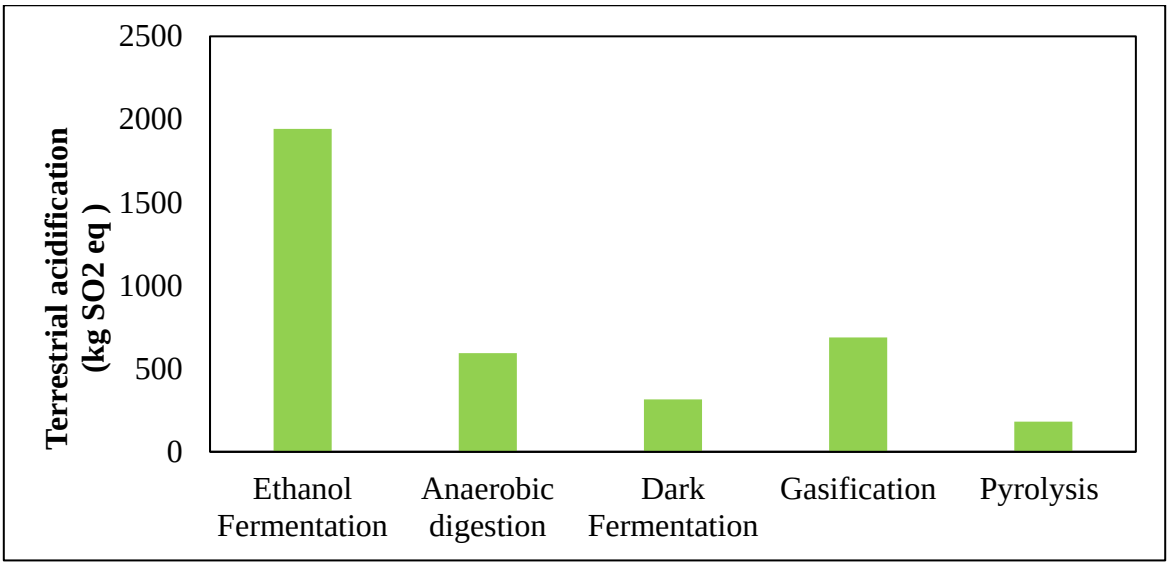

Figure 4-20: Terrestrial acidification impacts of the investigated process routes

The bioethanol fermentation process shows the highest terrestrial acidification impact (1942.88 kg SO_2 eq), followed by the gasification process (687.92 kg SO_2 eq) and the anaerobic digestion process (593.87 kg SO_2 eq). The dark fermentation process exhibits a terrestrial acidification impact of 315.56 kg SO_2 eq, while the pyrolysis process shows the lowest impact (181.47 kg SO_2 eq).

Freshwater eutrophication

Freshwater eutrophication refers to the process whereby water bodies receive excessive nutrient loads, particularly phosphorus, which promotes the growth of algae. Algal growth negatively affects water treatment for human consumption by increasing chemical usage and causing filter clogging. In addition, eutrophication reduces dissolved oxygen levels in water bodies, which can harm aquatic organisms and disrupt ecosystems. Freshwater eutrophication is measured in kilograms of phosphorus equivalent (kg P eq). Figure 4-21 presents the freshwater eutrophication impacts of the investigated process routes.

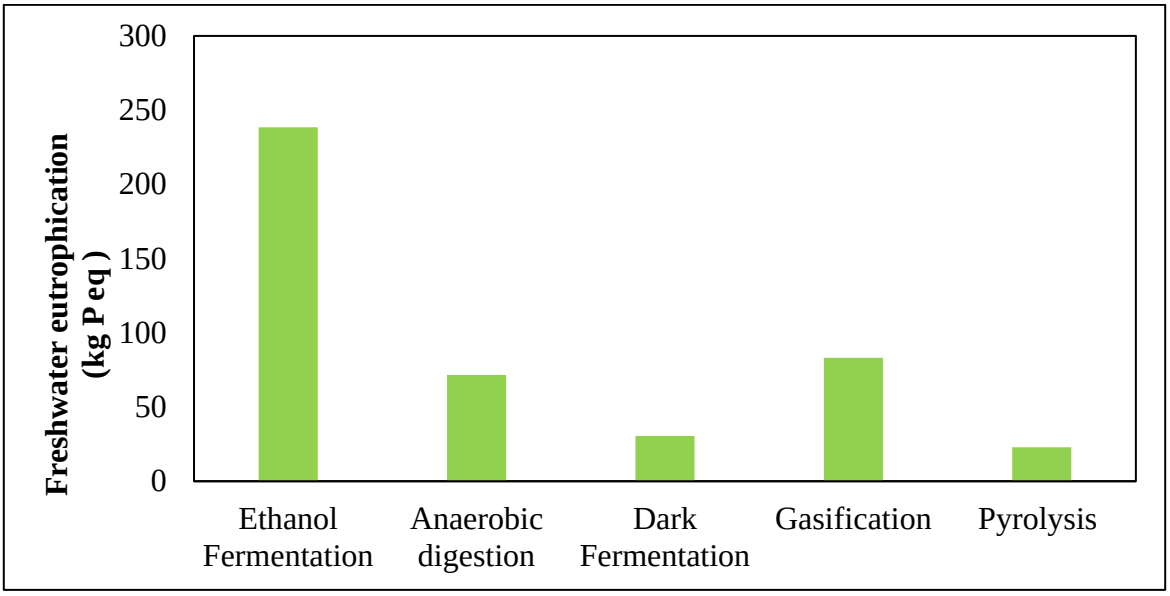

Figure 4-21: Freshwater eutrophication impacts of the investigated process routes

The pyrolysis process shows the lowest freshwater eutrophication impact, with a value of 22.82 kg P eq, followed by the dark fermentation process at 30.50 kg P eq. The anaerobic digestion process exhibits a freshwater eutrophication impact of 71.63 kg P eq, while the gasification process shows a value of 83.12 kg P eq. The bioethanol fermentation process has the highest freshwater eutrophication impact, with a value of 238.41 kg P eq.

Marine eutrophication

Marine eutrophication refers to the process whereby marine ecosystems become enriched with nutrients, particularly nitrogen. Excessive nutrient loading promotes algal growth in marine water bodies, which can lead to oxygen depletion and negatively affect aquatic organisms. Marine eutrophication is expressed in kilograms of nitrogen equivalent (kg N eq), which

quantifies the amount of nitrogen that would result in an equivalent eutrophication effect within a given system. Figure 4-22 presents the marine eutrophication impacts of the investigated process routes.

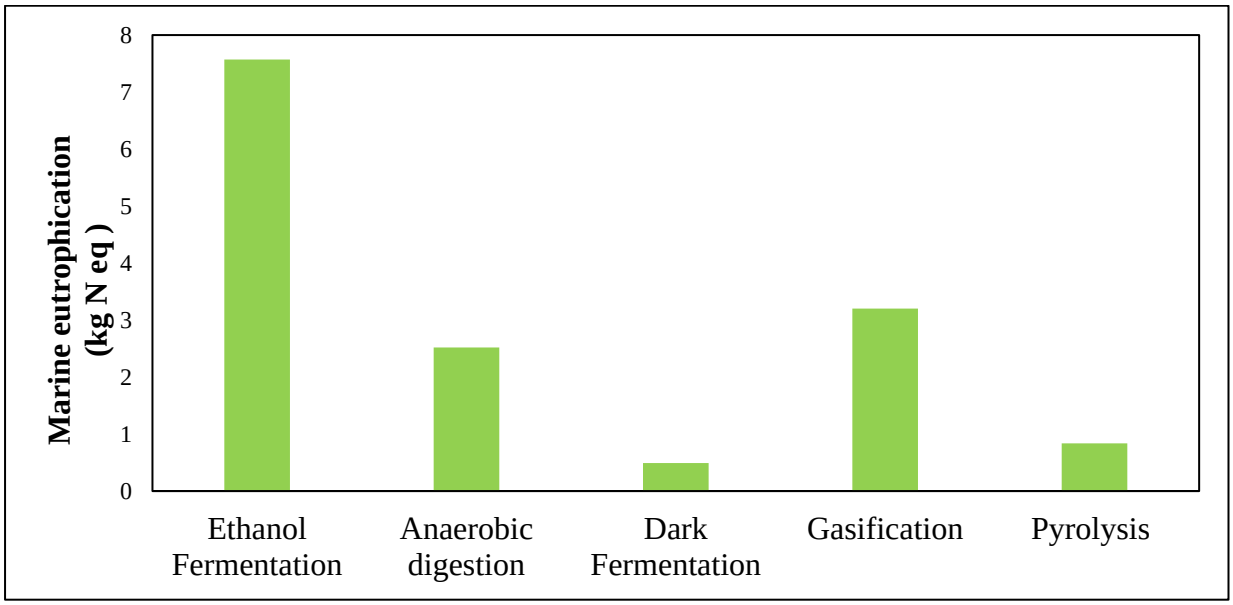

Figure 4-22: Marine eutrophication impacts of the investigated process routes

The marine eutrophication impacts of the investigated process routes were all below 10 kg nitrogen equivalent (kg N eq). The marine eutrophication values were 0.49 kg N eq, 0.84 kg N eq, 2.52 kg N eq, 3.20 kg N eq, and 7.57 kg N eq for the dark fermentation process, pyrolysis process, anaerobic digestion process, gasification process, and bioethanol fermentation process, respectively. The bioethanol fermentation process shows the highest marine eutrophication impact, while the pyrolysis and dark fermentation processes demonstrate the lowest contribution to marine eutrophication.

Mineral resource scarcity

Mineral resource scarcity refers to the limited availability or depletion of mineral resources used in various industrial applications. This impact category is measured in kilograms of copper equivalent (kg Cu eq), which represents resource depletion in terms of copper scarcity. Copper is commonly used as a reference metal in mineral scarcity assessments. Figure 4-23 presents the mineral resource scarcity impacts of the investigated process routes.

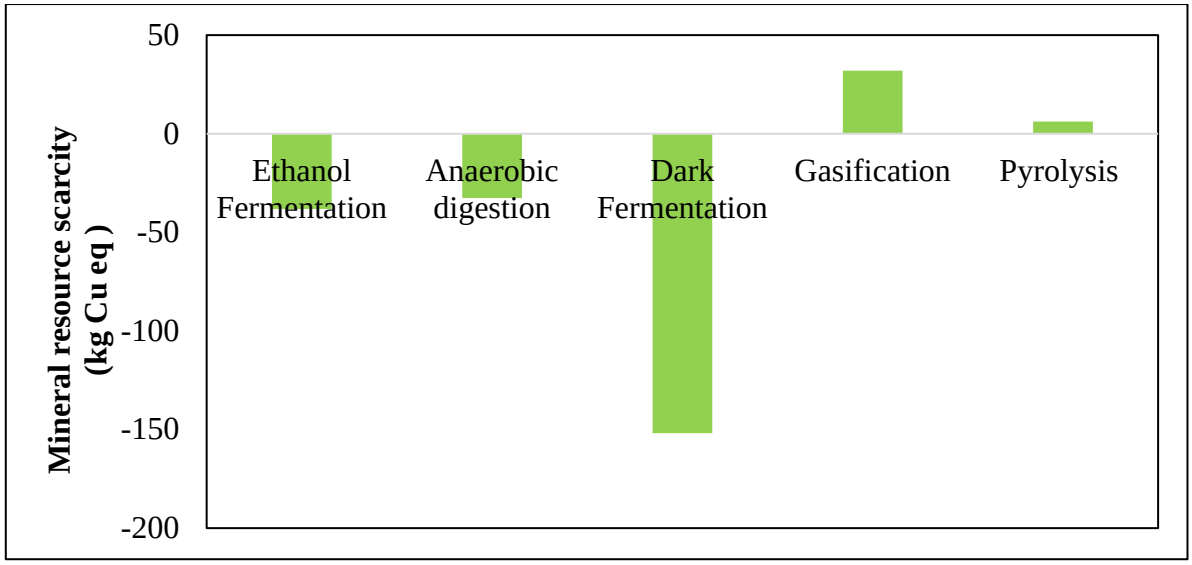

Figure 4-23: Mineral resource scarcity impacts of the investigated process routes

The mineral resource scarcity impacts of the investigated process routes may be attributed to the reliance of these processes on scarce minerals, either through equipment manufacturing, catalyst usage, or chemical reagents. These impacts could potentially be reduced through improved recycling strategies and the implementation of efficient material recovery techniques. The bioethanol fermentation process shows a negative mineral resource scarcity impact of −38.16 kg Cu eq. The gasification process, anaerobic digestion process, pyrolysis process, and dark fermentation process show mineral scarcity impacts of 31.95 kg Cu eq, −32.59 kg Cu eq, 6.17 kg Cu eq, and −151.84 kg Cu eq, respectively.

Fossil resource scarcity

Fossil resource scarcity refers to the limited availability or depletion of fossil resources used in various industrial applications. This impact category is measured in kilograms of oil equivalent (kg oil eq), which represents fossil fuel consumption associated with the investigated process routes. This indicator provides insight into the energy requirements and fossil fuel dependence of the processes. Figure 4-24 presents the fossil resource scarcity impacts of the investigated process routes.

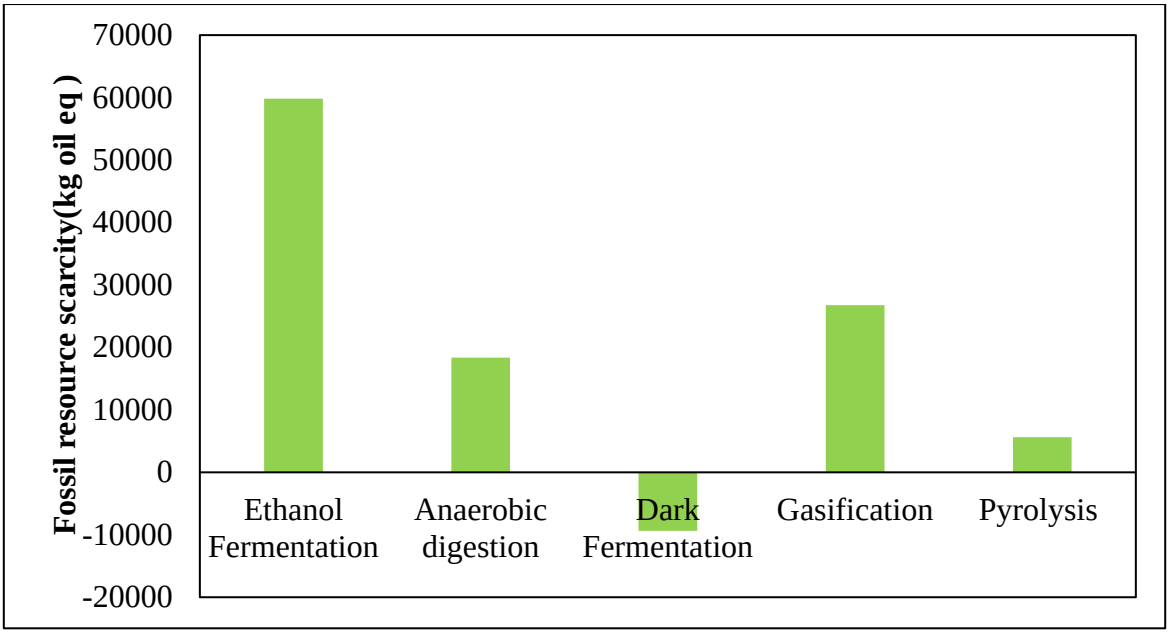

Figure 4-24: Fossil resource scarcity impacts of the investigated process routes

The bioethanol fermentation process shows the highest fossil resource scarcity impact among the evaluated processes, with a value of 59834.56 kg oil equivalent. This is due to the energy-intensive nature of bioethanol production, particularly during the pretreatment and purification stages. The gasification process shows a relatively high fossil resource scarcity impact of 26755.54 kg oil equivalent, although this is lower than that of the bioethanol fermentation process. Similar to ethanol fermentation, gasification is an energy-intensive process, as it requires biomass heating to approximately 800 °C. Electricity was assumed as the energy source across all simulated processes. It is therefore observed that processes that consume large amounts of energy tend to have higher fossil resource scarcity impacts.

The anaerobic digestion process shows a fossil resource scarcity impact of 18358.52 kg oil equivalent, which is lower than that of bioethanol fermentation and gasification due to its lower energy requirements. The dark fermentation process shows a negative fossil resource scarcity impact of −9366.12 kg oil equivalent, indicating environmental savings. This is attributed to its lower energy requirements compared to bioethanol fermentation, gasification, and anaerobic digestion. Additionally, the avoided product credits, particularly from acetic acid production, contribute to reduced impacts. The pyrolysis process shows a fossil resource scarcity impact of 5627.53 kg oil equivalent.

Water consumption

Water consumption of the investigated process routes is presented in cubic metres (m^3). This represents the total amount of water required for the investigated production processes and provides insight into environmental sustainability, as water usage is an important indicator in sustainability evaluation. Figure 4-25 presents the water consumption results for the investigated process routes.

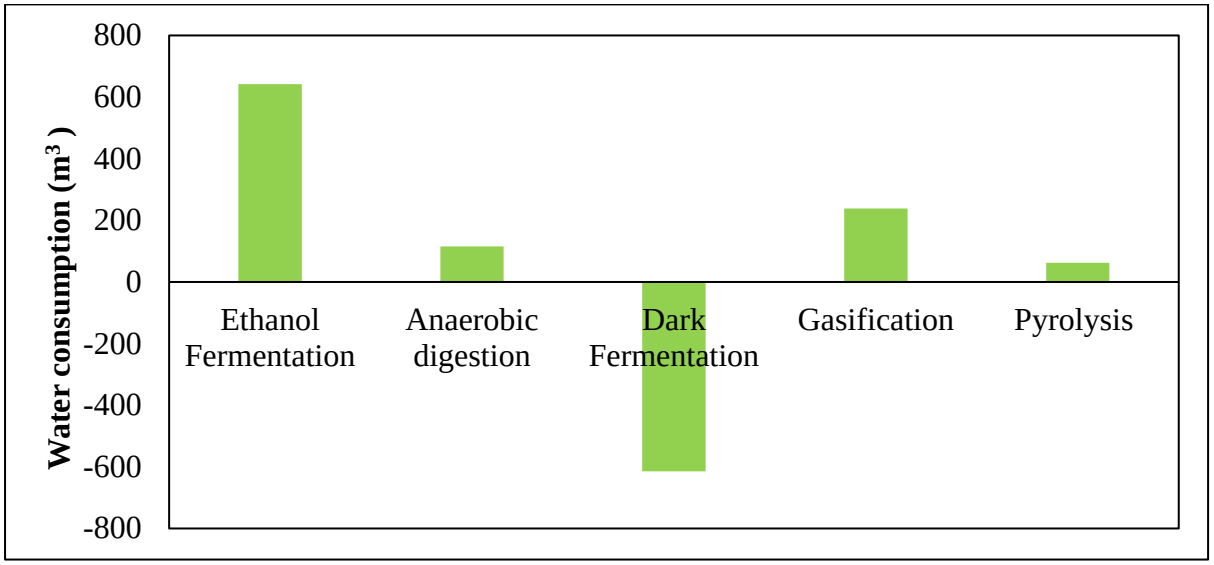

Figure 4-25: Water consumption impacts of the investigated process routes

The bioethanol fermentation process shows the highest water consumption among the investigated process routes, with a value of 642.20 m^3. This is mainly due to the steam requirements during pretreatment, as well as the water used in the scrubber for CO_2 removal. Furthermore, significant amounts of water are required in the distillation and rectification columns during the purification stage. The gasification process follows with a water consumption of 238.64 m^3, largely due to steam requirements, as steam is used as the gasification agent.

The anaerobic digestion process has a water requirement of 115.40 m^3. In anaerobic digestion, water is used during pretreatment for steam generation, and additional water is required for cooling the produced gas. The pyrolysis process shows a water consumption of 62.57 m^3, which is mainly associated with cooling requirements.

Lastly, the dark fermentation process exhibits a negative water consumption value of −614.74 m^3. Water is used in the pretreatment stage; however, a larger amount of water is generated during the process and is simulated as an avoided product, resulting in an overall negative water consumption value. Overall, the bioethanol fermentation process is the most water-intensive process route among those investigated.

4.4.3. Impact ranking of investigated processes

The overall ranking of the environmental impacts of the investigated process routes was performed relative to the most environmentally impactful process route in each category. The process route with the highest impact in each category was assigned a value of 100%, and the remaining process routes were rated relative to this reference value. The normalised scores are therefore considered unitless. Figure 4-26 presents a comparison of the environmental impact rankings of the investigated process routes.

Among the eight impact categories investigated, the bioethanol fermentation process is the major contributor to seven categories, with the exception of mineral resource scarcity. Mineral resource scarcity is the only category in which the bioethanol fermentation process exhibited a relatively minimal impact. In all other categories, the bioethanol fermentation process shows the highest environmental impacts. The total normalised scores were calculated for each investigated process route, and the results are presented in Table 4-20.

For normalisation and fairness, it was assumed that all impact categories are equivalent in terms of significance. The bioethanol fermentation process is the most environmentally impactful process route, with a total score of 581, followed by the gasification process with a score of 379. The anaerobic digestion process shows a moderate total score of 109. Both the dark fermentation process and the pyrolysis process exhibit the lowest total scores, with values of −544 and 88, respectively. This suggests that the dark fermentation and pyrolysis processes have lower overall environmental impacts compared to the other investigated process routes.

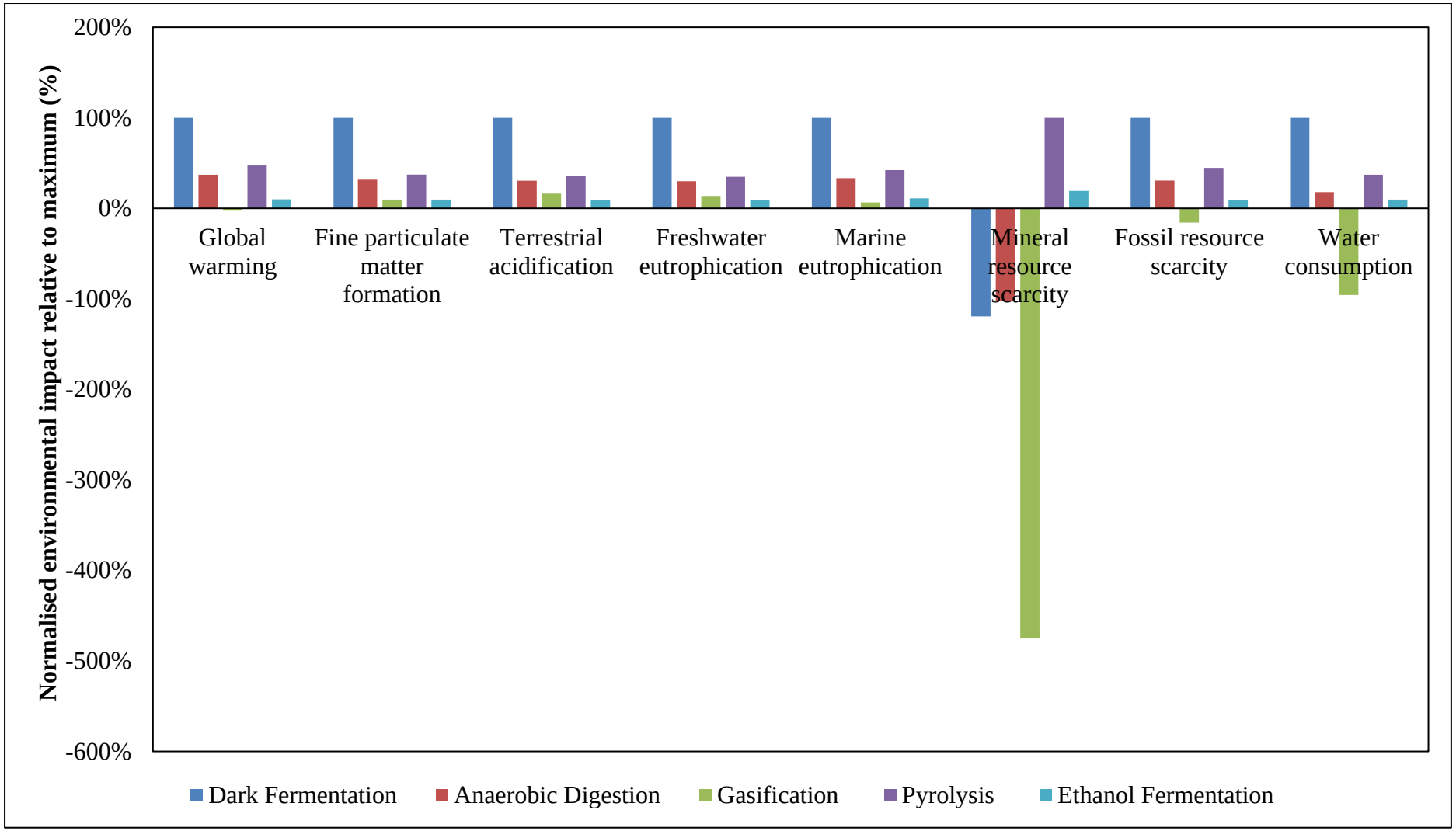

Figure 4-26: Comparison of the environmental impact category rankings of the investigated process routes

Table 4-20: The score totals of environmental impact for the investigated process routes

Impact category	Ethanol Fermentation	Anaerobic Digestion	Dark Fermentation	Gasification	Pyrolysis
Global warming	100%	37%	-3%	47%	10%
Fine particulate matter formation	100%	32%	10%	37%	10%
Terrestrial acidification	100%	31%	16%	35%	9%
Freshwater eutrophication	100%	30%	13%	35%	10%
Marine eutrophication	100%	33%	7%	42%	11%
Mineral resource scarcity	-119%	-102%	-475%	100%	19%
Fossil resource scarcity	100%	31%	-16%	45%	9%
Water consumption	100%	18%	-96%	37%	10%
Total score	**581%**	**109%**	**-544%**	**379%**	**88%**

4.5. Summary

This chapter presented the results of the study and discussed the mass and energy balances obtained from Aspen Plus process simulations of the investigated process routes, as well as the economic assessment and life cycle assessment. The highest yield was achieved through the fast pyrolysis process, which produced 0.27 tonnes of bio-oil per tonne of SCB and 0.09 tonnes of syngas per tonne of SCB. The gasification process produced 0.37 tonnes of syngas per tonne of SCB. The bioethanol fermentation process produced 0.20 tonnes of ethanol per tonne of SCB, while the anaerobic digestion process produced 0.10 tonnes of biogas per tonne of SCB. The dark fermentation process produced 0.025 tonnes of biohydrogen per tonne of SCB. The gasification process ranked second after the fast pyrolysis process, which produced the highest yields. For the purpose of recovering energy from sugarcane bagasse, both the fast pyrolysis and gasification processes are the most productive methods, as they generate multiple products.

Among the five investigated process routes, the bioethanol fermentation process had the highest energy demand, with a heating duty of 98.24 MWh, while the fast pyrolysis process had the lowest energy demand, with a heating duty of 9.77 MWh.The economic assessment evaluated four economic indicators using discounted cash flow analysis, namely NPV, PBP, ROI, and PI. Under the conditions assumed in this study, the bioethanol fermentation process was found to be economically unfeasible, as it produced a negative NPV. This indicates that the project would not be able to recover its initial investment costs at the end of the plant lifetime, which was assumed to be 25 years in this study. The fast pyrolysis process was

identified as the most profitable and promising option, achieving the highest NPV of 199.44 million USD (R36.62 billion), the lowest payback period of 1 year, the highest ROI of 10.27, and the highest PI of 46.64.

The bioethanol fermentation process consistently exhibited the highest environmental impacts across most evaluated impact categories, primarily due to its high energy demand. The dark fermentation process was identified as the best-performing option from an environmental perspective, as it consistently demonstrated environmental savings due to its lower energy requirements and the presence of value-added co-products such as acetic acid, water, and digestate. These co-products were simulated as avoided products. The fast pyrolysis process was the second-best performing route environmentally, consistently showing low impacts across several impact categories. When both environmental and economic performance are considered, the fast pyrolysis process emerges as the most favourable overall option.

However, the feasibility of these processing routes is also influenced by feedstock availability and seasonal variation. Sugarcane bagasse production is dependent on the sugarcane harvesting and milling season, which may result in fluctuations in feedstock supply throughout the year. This seasonality may require additional storage infrastructure, increased handling costs, or alternative feedstock integration to ensure continuous plant operation. Therefore, feedstock seasonality is an important factor that should be considered when selecting the most suitable processing route for industrial implementation (Kadwa 2013; Pippo *et al.* 2014; Formann *et al.* 2020; de Carvalho *et al.* 2023).

In addition, the marketability of the produced biofuels is critical for the commercial viability of the proposed biorefineries. Although fast pyrolysis produced the highest yield of bio-oil, the commercial utilisation of bio-oil is dependent on its stability, upgrading requirements, transportation constraints, and the availability of suitable end-user markets. Similarly, despite biohydrogen being a clean and high-value fuel, its marketability is limited by challenges associated with storage, compression, distribution infrastructure, and safety considerations. Therefore, the commercial deployment of bio-oil and biohydrogen production routes may require further evaluation of product upgrading requirements and market demand to enhance overall feasibility (Pinheiro Pires *et al.* 2019; Sanchez-Borrego, Alvarez-Mateos, and Garcia-Martin 2021; Inayat *et al.* 2022; Lachos-Perez *et al.* 2023; Mohanty *et al.* 2024; Parvari, Mahajan and Hewitt 2025).

Chapter 5: Conclusions and Recommendations

The study focused on the techno-economic assessment of biofuels produced from sugarcane bagasse, together with a life cycle assessment. This chapter discusses the key results of the study, providing a comprehensive understanding of the potential and challenges associated with different bio-based production routes. It also highlights areas for future focus and investment to optimise returns and sustainability.

5.1. Conclusions

Five sugarcane bagasse-to-biofuel processes were investigated. These included fermentation for bioethanol production, anaerobic digestion (biogas production), dark fermentation (biohydrogen production), gasification, and fast pyrolysis. The process simulations of the investigated process routes were performed using Aspen Plus V11 in order to obtain mass and energy balances. Aspen Process Economic Analyzer (APEA) was used to estimate installed equipment costs. These equipment costs were then used to estimate additional capital and operating costs, which enabled an economic assessment using the discounted cash flow analysis method. Four economic indicators were evaluated, namely net present value (NPV), payback period (PBP), return on investment (ROI), and profitability index (PI). Furthermore, life cycle assessment (LCA) was performed to evaluate the environmental impacts of the investigated process routes. SimaPro software was used for the LCA, following the ISO 14040 and ISO 14044 methodology.

Based on the findings of this study, the following conclusions were reached:

- Abundant sugarcane bagasse, a lignocellulosic by-product of the sugar industry, is available for conversion to biofuels. This could allow sugar mills to develop biorefineries annexed to existing operations. The study considered processing the remaining portion of sugarcane bagasse produced in the sugar mill, with the balance utilised for steam production

- The utilisation of process simulation software such as Aspen Plus reduces expenses incurred during the research and development process. Aspen Plus allows for the comprehensive evaluation of processes, including the estimation of product yields,

energy requirements, and economic feasibility. Furthermore, Aspen Plus enables process optimisation and sensitivity analysis.

- Sugarcane bagasse is a potential biomass feedstock for annexed biorefineries at sugar mills. A single feedstock can be used to produce a variety of value-added products as well as biofuels. Fermentation produced bioethanol, anaerobic digestion produced biogas, dark fermentation produced biohydrogen, gasification produced syngas and biochar, whereas fast pyrolysis produced three valuable products, namely bio-oil, syngas, and biochar.

- The feasibility of the processes was highly dependent on product yields, the selling price of final products, capital expenditure (CAPEX), and operating expenses (OPEX).

- Discount rate is another sensitive parameter that should be carefully selected when using discounted cash flow analysis for economic evaluation. A higher discount rate reduces the projected economic benefits of the processes. Selecting a lower discount rate may create unrealistic expectations, as lower discount rates result in higher projected returns.

- Bioethanol production via fermentation was not feasible under the conditions assumed in this study due to high investment costs, high energy demand, and low product yields. Ethanol ranked third in terms of product yield. In addition, the process exhibited the highest environmental impacts due to its high energy requirements.

- Although biogas production via anaerobic digestion resulted in a lower product yield compared to bioethanol, it was found to be feasible due to its relatively low CAPEX and OPEX, as well as reduced energy demands compared to bioethanol production.

- Biohydrogen production via dark fermentation was found to be a feasible project due to its high co-product yields and high selling price. The process produced acetic acid in significant quantities, which improved its economic feasibility. It was noted that without acetic acid production, the process would not be feasible due to the low yield

of biohydrogen. The process also had minimal energy demand, which further contributed to its feasibility.

- A gasification biorefinery annexed to the sugar mill was also identified as a feasible project, with a payback period of 3.6 years.

- Fast pyrolysis was identified as the most feasible process, achieving the highest profitability index (PI) of 46.64. This was followed by biohydrogen production via dark fermentation with acetic acid co-production, which ranked second with a PI of 7.95. Gasification ranked third in terms of feasibility, followed by anaerobic digestion in fourth position.

- The environmental impacts were strongly influenced by energy consumption, as electricity was used as the primary energy source in the LCA. The results suggest that processes with high energy demand contribute more significantly to environmental impacts, mainly because electricity generation in South Africa is largely coal-based.

- Electricity consumption was found to be the largest contributor to environmental impacts, due to coal-based electricity production. Therefore, processes with high electricity consumption resulted in higher environmental impacts, making them less environmentally favourable. The bioethanol fermentation process, which had the highest electricity demand, also exhibited the highest environmental impacts. This indicates that it is not only economically unfeasible but also environmentally unfavourable due to the high energy demands of pretreatment and purification stages.

- Among the investigated processes, biohydrogen production via dark fermentation was the most environmentally friendly process route, followed by fast pyrolysis.

- Overall, both biohydrogen production via dark fermentation and fast pyrolysis were found to be economically feasible and environmentally favourable, making them promising process routes with significant potential.

5.2. Recommendations

Future research on the conversion of sugarcane bagasse may benefit from the following recommendations, which may assist in addressing the gaps identified during this study:

- Future studies should consider conducting laboratory experiments before performing simulations to ensure that the selected process conditions can be maintained and that all required simulation data are available.

- Experimental data for biohydrogen production via dark fermentation are limited. Further studies should be conducted to ensure more accurate approximations. In addition, the recovery of acetic acid should be investigated further, as it contributes significantly to the economic feasibility of the dark fermentation process.

- Future experimental studies are encouraged to assess the integration of two or more processes. Anaerobic digestion has been reported as a potential pretreatment step for biological processes. This suggests that a production configuration could begin with anaerobic digestion followed by fermentation for bioethanol production, for example. Such integration may reduce the heat duty required for steam explosion, which was adopted in the current study.

- Future studies should assess the feasibility of annexing biorefineries to existing sugar mills and investigate the availability of space within the sugar mill for such integration.

- All biological process routes produce carbon dioxide as a by-product. Carbon dioxide is a greenhouse gas that accounts for approximately 80% of greenhouse gas emissions. However, carbon dioxide also has several industrial applications. In this study, it was assumed that carbon dioxide would be supplied to concrete manufacturing companies. It is recommended that carbon capture technologies be investigated further.

- In this study, feedstock costs were assumed to be negligible, as the biorefineries were assumed to be annexed to the sugar mill. It is recommended that future studies

investigate scenarios in which sugarcane bagasse is sold as feedstock to the biorefinery, since feedstock cost can significantly affect the break-even point.

- The study also indicated that economic performance is significantly influenced by fixed capital investment and operating expenses. These cost components should be prioritised in process optimisation, particularly for bioethanol fermentation, which exhibited high values for both CAPEX and OPEX.

- Future studies should assess the impact of integrating renewable electricity sources, such as solar photovoltaic (PV) systems, into the biorefinery. This could reduce reliance on grid electricity and may significantly decrease environmental impacts, particularly in the global warming potential, fossil resource scarcity, and fine particulate matter formation categories.

References

Abdo, S. M., Ahmed, E., El-Enin, S. A., El Diwan, G., El-Khatib, K., Ali, G. H. and El Din, R. A. S. 2022. Algal fuel production by industry: Process simulation and economic assessment. In: *Handbook of Algal Biofuels*. Elsevier, 635-652.

Abdool Karim, S., Kruger, P. and Hofman, K. 2020. Industry strategies in the parliamentary process of adopting a sugar-sweetened beverage tax in South Africa: a systematic mapping. *Globalization and Health*, 16 (1): 1-14.

Abdullah, B., Muhammad, S. A. F. a. S., Shokravi, Z., Ismail, S., Kassim, K. A., Mahmood, A. N. and Aziz, M. M. A. 2019. Fourth generation biofuel: A review on risks and mitigation strategies. *Renewable and Sustainable Energy Reviews*, 107: 37-50.

Abo, B. O., Gao, M., Wang, Y., Wu, C., Ma, H. and Wang, Q. 2019. Lignocellulosic biomass for bioethanol: an overview on pretreatment, hydrolysis and fermentation processes. *Reviews on Environmental Health*, 34 (1): 57-68.

Adarme, O. F. H., Baêta, B. E. L., Lima, D. R. S., Gurgel, L. V. A. and de Aquino, S. F. 2017. Methane and hydrogen production from anaerobic digestion of soluble fraction obtained by sugarcane bagasse ozonation. *Industrial Crops and Products*, 109: 288-299.

Aden, A. and Foust, T. 2009. Technoeconomic analysis of the dilute sulfuric acid and enzymatic hydrolysis process for the conversion of corn stover to ethanol. *Cellulose*, 16 (4): 535-545.

Adeoye, A. O., Lawal, O. S., Quadri, R. O., Malomo, D., Aliyu, M. T., Dang, G. E., Emojevu, E. O., Maikato, M. J., Yahaya, M. G. and Omonije, O. O. 2023. Sustainable Energy via Thermochemical and Biochemical Conversion of Biomass Wastes for Biofuel Production. In: *Transportation Energy and Dynamics*. Springer, 245-306.

Admasu, A., Bogale, W. and Mekonnen, Y. S. 2022. Experimental and simulation analysis of biogas production from beverage wastewater sludge for electricity generation. *Scientific Reports*, 12 (1): 9107.

Agbor, V. B., Cicek, N., Sparling, R., Berlin, A. and Levin, D. B. 2011. Biomass pretreatment: fundamentals toward application. *Biotechnology Advances*, 29 (6): 675-685.

Agrawal, R., Verma, A., Singhania, R. R., Varjani, S., Di Dong, C. and Patel, A. K. 2021. Current understanding of the inhibition factors and their mechanism of action for the lignocellulosic biomass hydrolysis. *Bioresource Technology*, 332: 125042.

Ahmad, A., Rambabu, K., Hasan, S. W., Show, P. L. and Banat, F. 2024. Biohydrogen production through dark fermentation: Recent trends and advances in transition to a circular bioeconomy. *International Journal of Hydrogen Energy*, 52: 335-357.

Ahmad, W., Ahmad, A., Ostrowski, K. A., Aslam, F., Joyklad, P. and Zajdel, P. 2021. Sustainable approach of using sugarcane bagasse ash in cement-based composites: A systematic review. *Case Studies in Construction Materials*, 15: 1-28.

Ahmadi, F., Zamiri, M. J., Khorvash, M., Ziaee, E. and Polikarpov, I. 2016. Pre-treatment of sugarcane bagasse with a combination of sodium hydroxide and lime for improving the ruminal degradability: Optimization of process parameters using response surface methodology. *Journal of Applied Animal Research*, 44 (1): 287-296.

Ahmed, M. A., Rehman, M. S. U., Terán-Hilares, R., Khalid, S. and Han, J.-I. 2017. Optimization of twin gear-based pretreatment of rice straw for bioethanol production. *Energy Conversion and Management*, 141: 120-125.

Ajala, E., Ighalo, J., Ajala, M., Adeniyi, A. and Ayanshola, A. 2021. Sugarcane bagasse: a biomass sufficiently applied for improving global energy, environment and economic sustainability. *Bioresources and Bioprocessing*, 8 (1): 1-25.

Akhlaghi, N. and Najafpour-Darzi, G. 2020. A comprehensive review on biological hydrogen production. *International Journal of Hydrogen Energy*, 45 (43): 22492-22512.

Akhtar, A., Krepl, V. and Ivanova, T. 2018. A combined overview of combustion, pyrolysis, and gasification of biomass. *Energy & Fuels*, 32 (7): 7294-7318.

Al-Mawali, K. S., Osman, A. I., Ala'a, H., Mehta, N., Jamil, F., Mjalli, F., Vakili-Nezhaad, G. R. and Rooney, D. W. 2021. Life cycle assessment of biodiesel production utilising waste date seed oil and a novel magnetic catalyst: A circular bioeconomy approach. *Renewable Energy*, 170: 832-846.

Alkaya, E., Kaptan, S., Ozkan, L., Uludag-Demirer, S. and Demirer, G. N. 2009. Recovery of acids from anaerobic acidification broth by liquid–liquid extraction. *Chemosphere*, 77 (8): 1137-1142.

Amezcua-Allieri, M. A., Martínez-Hernández, E., Anaya-Reza, O., Magdaleno-Molina, M., Melgarejo-Flores, L. A., Palmerín-Ruiz, M. E., Eguía-Lis, J. A. Z., Rosas-Molina, A., Enríquez-Poy, M. and Aburto, J. 2019. Techno-economic analysis and life cycle assessment for energy generation from sugarcane bagasse: Case study for a sugar mill in Mexico. *Food and Bioproducts Processing*, 118: 281-292.

An, Q., Bu, J., Cheng, J.-R., Hu, B.-B., Wang, Y.-T. and Zhu, M.-J. 2020. Biological saccharification by Clostridium thermocellum and two-stage hydrogen and methane production from hydrogen peroxide-acetic acid pretreated sugarcane bagasse. *International Journal of Hydrogen Energy*, 45 (55): 30211-30221.

Ananthi, V., Bora, A., Ramesh, U., Yuvakkumar, R., Raja, K., Ponnuchamy, K., Muthusamy, G. and Arun, A. 2024a. A review on the technologies for sustainable biohydrogen production. *Process Safety and Environmental Protection*, 186: 944-956.

Ananthi, V., Ramesh, U., Balaji, P., Kumar, P., Govarthanan, M. and Arun, A. 2024b. A review on the impact of various factors on biohydrogen production. *International Journal of Hydrogen Energy*, 52: 33-45.

Angelonidi, E. and Smith, S. R. 2015. A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. *Water and Environment Journal*, 29 (4): 549-557.

Anju, A. J., Binod, P. and Pandey, A. 2017. Production and characterisation of microbial poly-y-glutamic acid from renewable resources. *Indian Journal of Experimental Biology*, 55: 405-410.

Anwar, Z., Gulfraz, M. and Irshad, M. 2014. Agro-industrial lignocellulosic biomass a key to unlock the future bio-energy: a brief review. *Journal of Radiation Research and Applied Sciences*, 7 (2): 163-173.

Aro, E.-M. 2016. From first generation biofuels to advanced solar biofuels. *Ambio*, 45 (Suppl 1): 24-31.

Atasoy, M., Owusu-Agyeman, I., Plaza, E. and Cetecioglu, Z. 2018. Bio-based volatile fatty acid production and recovery from waste streams: Current status and future challenges. *Bioresource Technology*, 268: 773-786.

Athira, G., Bahurudeen, A. and Appari, S. 2021. Thermochemical conversion of sugarcane bagasse: composition, reaction kinetics, and characterisation of by-products. *Sugar Tech*, 23: 433-452.

Aui, A., Wang, Y. and Mba-Wright, M. 2021. Evaluating the economic feasibility of cellulosic ethanol: A meta-analysis of techno-economic analysis studies. *Renewable and Sustainable Energy Reviews*, 145: 111098.

Awasthi, M. K., Sar, T., Gowd, S. C., Rajendran, K., Kumar, V., Sarsaiya, S., Li, Y., Sindhu, R., Binod, P. and Zhang, Z. 2023. A comprehensive review on thermochemical, and biochemical conversion methods of lignocellulosic biomass into valuable end product. *Fuel*, 342: 127790.

Awogbemi, O., Kallon, D. V. V., Onuh, E. I. and Aigbodion, V. S. 2021. An overview of the classification, production and utilization of biofuels for internal combustion engine applications. *Energies*, 14 (18): 5687.

Azhara, S. H. M., Abdullaa, R., Jamboa, S. A., Marbawia, H., Gansaua, J. A., Faika, A. A. M. and Rodriguesc, K. F. 2017. Yeasts in sustainable bioethanol production: A review. *Biochemistry and Biophysics Reports*, 10: 52-61.

Azman, S. 2016. Anaerobic digestion of cellulose and hemicellulose in the presence of humic acids. Doctoral, Wageningen University. Available: https://library.wur.nl/WebQuery/wurpubs/fulltext/392752 (Accessed 08/11/2021).

Azman, S., Khadem, A. F., Van Lier, J. B., Zeeman, G. and Plugge, C. M. 2015. Presence and role of anaerobic hydrolytic microbes in conversion of lignocellulosic biomass for biogas production. . *Environmental Science Technology* 45 (23): 2523-2564.

Bahlawan, Z. A. S., Damayanti, A., Putri, R. D. A., Triwibowo, B., Prasetiawan, H., Aji, S. P. K. and Prawisnu, A. 2022. Bioethanol production from glucose obtained from enzymatic hydrolysis of Chlorella microalgae. *Materials Today: Proceedings*, 63: S373-S378.

Bahú, J. O., de Oliveira, R. A., De Souza, L. M. A., Rivera, E. C., Felisbino, R. F., Maciel Filho, R. and Tovar, L. P. 2022. Kinetic study of thermal decomposition of sugarcane bagasse pseudo-components at typical pretreatment conditions: Simulations of opportunities towards the establishment of a feasible primary biorefining. *Cleaner Chemical Engineering*, 4: 100074.

Bakhiet, S. E. and Mahmoud, M. A. 2015. Production of bio-ethanol from molasses by Schizosaccharomyces species. *Annual Research & Review in Biology*, 7 (1): 45-53.

Banerjee, S., Pandit, C., Gundupalli, M. P., Pandit, S., Rai, N., Lahiri, D., Chaubey, K. K. and Joshi, S. J. 2023. Life cycle assessment of revalorization of lignocellulose for the development of biorefineries. *Environment, Development and Sustainability*, 26: 16387–16418.

Barahmand, Z. and Eikeland, M. S. 2022. Techno-Economic and Life Cycle Cost Analysis through the Lens of Uncertainty: A Scoping Review. *Sustainability*, 14 (19): 12191.

Baral, N. R. and Shah, A. 2017. Techno-economic analysis of utilization of stillage from a cellulosic biorefinery. *Fuel Processing Technology*, 166: 59-68.

Baral, P., Munagala, M., Shastri, Y., Kumar, V. and Agrawal, D. 2021. Cost reduction approaches for fermentable sugar production from sugarcane bagasse and its impact on techno-economics and the environment. *Cellulose*, 28 (10): 6305-6322.

Barta, Z., Reczey, K. and Zacchi, G. 2010. Techno-economic evaluation of stillage treatment with anaerobic digestion in a softwood-to-ethanol process. *Biotechnology for Biofuels*, 3 (1): 1-11.

Beig, B., Riaz, M., Naqvi, S. R., Hassan, M., Zheng, Z., Karimi, K., Pugazhendhi, A., Atabani, A. and Chi, N. T. L. 2021. Current challenges and innovative developments in pretreatment of lignocellulosic residues for biofuel production: A review. *Fuel*, 287: 119670.

Bernstad Saraiva, A. 2017. System boundary setting in life cycle assessment of biorefineries: a review. *International Journal of Environmental Science and Technology*, 14 (2): 435-452.

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S. and Iyyappan, J. 2018. Biogas production–A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and Sustainable Energy Reviews*, 90 (April): 570-582.

Bhutto, A. W., Qureshi, K., Harijan, K., Abro, R., Abbas, T., Bazmi, A. A., Karim, S. and Yu, G. 2017. Insight into progress in pre-treatment of lignocellulosic biomass. *Energy*, 122: 724-745.

Bordonal, R. d. O., Carvalho, J. L. N., Lal, R., de Figueiredo, E. B., de Oliveira, B. G. and La Scala, N. 2018. Sustainability of sugarcane production in Brazil. A review. *Agronomy for Sustainable Development*, 38: 1-23.

Boshagh, F., van Niel, E. and Lee, C.-J. 2025. Techno-economic and life-cycle analyses of dark fermentative hydrogen production integrated with anaerobic digestion from coffee-manufacturing wastewater under thermophilic and mesophilic conditions. *Bioresource Technology*, 416: 131737.

Bragança, I., Sánchez-Soberón, F., Pantuzza, G. F., Alves, A. and Ratola, N. 2020. Impurities in biogas: Analytical strategies, occurrence, effects and removal technologies. *Biomass and Bioenergy*, 143: 105878.

Brennan, D. 2020. *Process industry economics: principles, concepts and applications*. Elsevier.

Bridgwater, A. V. 2012. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, 38: 68-94.

Caroço, R. F. 2019. Model-based Monitoring and Optimization of a Bio-based Process. Technical University of Denmark.

Carpio, R., Secchi, S., Barros, R., Oliveira, R., Queiroz, S., Teixeira, R., Bon, E. and Secchi, A. 2022. Techno-economic evaluation of second-generation ethanol from sugarcane bagasse: Commercial versus on-site produced enzymes and use of the xylose liquor. *Journal of Cleaner Production*, 369: 133340.

Carrasco, C., Baudel, H. M., Sendelius, J., Modig, T., Roslander, C., Galbe, M., Hahn-Hägerdal, B., Zacchi, G. and Lidén, G. 2010. SO2-catalyzed steam pretreatment and fermentation of enzymatically hydrolyzed sugarcane bagasse. *Enzyme and Microbial Technology*, 46 (2): 64-73.

Cazier, E. A., Trably, E., Steyer, J.-P. and Escudie, R. 2019. Reversibility of hydrolysis inhibition at high hydrogen partial pressure in dry anaerobic digestion processes fed with wheat straw and inoculated with anaerobic granular sludge. *Waste Management*, 85: 498-505.

Cesaro, A. and Belgiorno, V. 2015. Combined biogas and bioethanol production: Opportunities and challenges for industrial application. *Energies*, 8 (8): 8121-8144.

Cespi, D. 2024. Procedural life cycle inventory of chemical products at laboratory and pilot scale: a compendium. *Green Chemistry*, 26 (18): 9554-9568.

Chand, K., Arora, D. and Sharma, S. 2024. Study on the performance of sugarcane juice clarifier. *African Journal of Biological Sciences*, 6: 1021-1030.

Chandel, A. K., Da Silva, S. S. and Singh, O. V. 2013. Detoxification of lignocellulose hydrolysates: biochemical and metabolic engineering toward white biotechnology. *BioEnergy Research*, 6: 388-401.

Chaturvedi, V. and Verma, P. 2013. An overview of key pretreatment processes employed for bioconversion of lignocellulosic biomass into biofuels and value added products. *Biotech*, 3: 415-431.

Chaudhary, S., Jain, V. P. and Jaiswar, G. 2022. The composition of polysaccharides: monosaccharides and binding, group decorating, polysaccharides chains. In: *Innovation in Nano-Polysaccharides for Eco-sustainability*. Elsevier, 83-118.

ChemAnalyst. 2024. *Acetic acid Proce Trend and Forecast*. Available: https://www.chemanalyst.com/Pricing-data/acetic-acid-9 (Accessed 09 November 2024).

Chen, D., Zhuang, X., Gan, Z., Cen, K., Ba, Y. and Jia, D. 2022a. Co-pyrolysis of light bio-oil leached bamboo and heavy bio-oil: Effects of mass ratio, pyrolysis temperature, and residence time on the biochar. *Chemical Engineering Journal*, 437: 135253.

Chen, W.-H., Nižetić, S., Sirohi, R., Huang, Z., Luque, R., Papadopoulos, A. M., Sakthivel, R., Nguyen, X. P. and Hoang, A. T. 2022b. Liquid hot water as sustainable biomass pretreatment technique for bioenergy production: A review. *Bioresource Technology*, 344: 126207.

Cheng, Y., Zhang, H., Xu, Z. and Wu, L. 2018. *Advanced applications of lignin-based materials*.

Chong, C. T., Mong, G. R., Ng, J. H., Chong, W. W. F., Ani, F. N., Lam, S. S. and Ong, H. C. 2019. Pyrolysis characteristics and kinetic studies of horse manure using thermogravimetric analysis. *Energy Conversion Managemant*, 180: 1260-1267.

Choudhary, M., Joshi, S., Singh, P. and Srivastava, N. 2020. Biofuel production from lignocellulosic biomass: Introduction and metabolic engineering for fermentation scale-up. In: *Genetic and metabolic engineering for improved biofuel production from lignocellulosic biomass*. Elsevier, 1-12.

Chovau, S., Degrauwe, D. and Van der Bruggen, B. 2013. Critical analysis of techno-economic estimates for the production cost of lignocellulosic bio-ethanol. *Renewable and Sustainable Energy Reviews*, 26: 307-321.

Chowdhury, T. 2021. Technical-economical analysis of anaerobic digestion process to produce clean energy. *Energy Reports*, 7: 247-253.

Cleanhydrogenpartnership. 2024. *Hydrogen cost and sales prices*. Available: https://h2v.eu/analysis/statistics/financing/hydrogen-cost-and-sales-prices (Accessed 23 August 2024).

Clomburg, J. M., Crumbley, A. M. and Gonzalez, R. 2017. Industrial biomanufacturing: the future of chemical production. *Science*, 355 (6320): 804.

Corigliano, O., Iannuzzi, M., Pellegrino, C., D'Amico, F., Pagnotta, L. and Fragiacomo, P. 2023. Enhancing Energy Processes and Facilities Redesign in an Anaerobic Digestion Plant for Biomethane Production. *Energies*, 16 (15): 5782.

da Silva Fernandes, F., de Souza, É. S., Carneiro, L. M., Alves Silva, J. P., de Souza, J. V. B. and da Silva Batista, J. 2022. Current ethanol production requirements for the yeast Saccharomyces cerevisiae. *International Journal of Microbiology*, 2022.

da Silva, G. T., Chiarello, L. M., Lima, E. M. and Ramos, L. P. 2016. Sono-assisted alkaline pretreatment of sugarcane bagasse for cellulosic ethanol production. *Catalysis Today*, 269: 21-28.

Daramola, M. O., Sadare, O. O., Ejekwu, O., Moshokoa, M. F. and Jimoh, M. O. 2021. Membrane purification techniques for recovery of succinic acid obtained from fermentation broth during bioconversion of lignocellulosic biomass: current advances and future perspectives. 13 (12): 6794.

Darda, S., Papalas, T. and Zabaniotou, A. 2019. Biofuels journey in Europe: Currently the way to low carbon economy sustainability is still a challenge. *Journal of Cleaner Production*, 208: 575-588.

Das, S. K. and Ghosh, S. K. 2022. Thermodynamic analysis of biomass and plastic feedstock circulation using pyrolysis technology. *Circular Economy*, 1 (1): 100006.

de Carvalho, D. M., de Queiroz, J. H. and Colodette, J. L. 2016. Assessment of alkaline pretreatment for the production of bioethanol from eucalyptus, sugarcane bagasse and sugarcane straw. *Industrial Crops and Products*, 94: 932-941.

de Carvalho, J. C., de Souza Vandenberghe, L. P., Sydney, E. B., Karp, S. G., Magalhães Jr, A. I., Martinez-Burgos, W. J., Medeiros, A. B. P., Thomaz-Soccol, V., Vieira, S. and Letti, L. A. J. 2023. Biomethane production from sugarcane vinasse in a circular economy: Developments and innovations. *Fermentation*, 9 (4): 349.

de Souza Vandenberghe, L. P., Nelson Libardi Junior, C., Rodrigues, J. G. W. S. and Soccol, C. R. 2020. Fermentation Strategies to Minimize Product Inhibition in Bioethanol Production. *Enzyme Inhibition-Environmental and Biomedical Applications*, 1: 148-173.

Demirbas, A. and Arin, G. 2002. An overview of biomass pyrolysis. *Energy sources*, 24 (5): 471-482.

DepartmentofAgriculture, F. Agriculture, F. a. F. 2014. *Sugarcane production guideline*. Department of Agriculture, Forestry and Fisheries. Available: https://www.dalrrd.gov.za/Portals/0/Brochures%20and%20Production%20guidelines/sugar%20cane%20prodocution%20%20guideline.pdf (Accessed 17 September 2021).

DepartmentofTradeIndustryandCompetition. 2020. *South African Sugar Value Chain Master Plan 2030*. Available: https://www.thedtic.gov.za/wp-content/uploads/Masterplan-Sugar.pdf (Accessed April/23/2023).

Detsios, N., Maragoudaki, L., Rebecchi, S., Quataert, K., De Winter, K., Stathopoulos, V., Orfanoudakis, N. G., Grammelis, P. and Atsonios, K. 2024. Techno-Economic Evaluation of Jet Fuel Production via an Alternative Gasification-Driven Biomass-to-Liquid Pathway and Benchmarking with the State-of-the-Art Fischer–Tropsch and Alcohol-to-Jet Concepts. *Energies*, 17 (7): 1685.

Di Stasi, C., Cortese, M., Greco, G., Renda, S., Gonzalez, B., Palma, V. and Manya, J. J. 2021. Optimization of the operating conditions for steam reforming of slow pyrolysis oil over an activated biochar-supported Ni–Co catalyst. *International Journal of Hydrogen Energy*, 46 (53): 26915-26929.

Diao, Y. and Yang, H. 2021. Gas-cleaning technology. In: *Industrial Ventilation Design Guidebook*. Elsevier, 279-371.

Dias, M. O., Ensinas, A. V., Nebra, S. A., Maciel Filho, R., Rossell, C. E. and Maciel, M. R. W. 2009. Production of bioethanol and other bio-based materials from sugarcane bagasse: integration to conventional bioethanol production process. *Chemical Engineering Research and Design*, 87 (9): 1206-1216.

Dibazar, A. S., Aliasghar, A., Behzadnezhad, A., Shakiba, A. and Pazoki, M. 2023. Energy cycle assessment of bioethanol production from sugarcane bagasse by life cycle approach using the fermentation conversion process. *Biomass Conversion and Biorefinery*, 14: 20679–20698.

Dogbe, E. S., Mandegari, M. A. and Görgens, J. F. 2018. Exergetic diagnosis and performance analysis of a typical sugar mill based on Aspen Plus® simulation of the process. *Energy*, 145: 614-625.

Drosg, B., Fuchs, W., Meixner, K., Waltenberger, R., Kirchmayr, R., Braun, R. and Bochmann, G. 2013. Anaerobic digestion of stillage fractions–estimation of the potential for energy recovery in bioethanol plants. *Water Science and Technology*, 67 (3): 494-505.

El Asri, O. 2022. Anaerobic biodegradation: the anaerobic digestion process. In: *Handbook of Biodegradable Materials*. Springer, 1-26.

Elbasiouny, H., A.Elbanna, B., Al-Nourli, E., Alsherief, A., Negm, S., El-Nour, E. A., Nofal, A. and Sharabash, S. 2020. Agricultural Waste Management for Climate Change Mitigation:Some Implications to Egypt. In: *Waste Management in MENA Regions*. Tanta: Springer Nature Switzerland AG, 149-196.

Elliott, D. C., Biller, P., Ross, A. B., Schmidt, A. J. and Jones, S. B. 2015. Hydrothermal liquefaction of biomass: Developments from batch to continuous process. *Bioresource Technology*, 178: 147-156.

EThekwiniMunicipality. 2024. *Tariff Tables 2024/2025*. Available: https://www.durban.gov.za/storage/Documents/Budget%20Reports/Tariffs/Final%20TARIFF%20TABLES%202024-2025.pdf (Accessed 25 June 2024).

Feng, Y.-H., Cheng, T.-Y., Yang, W.-G., Ma, P.-T., He, H.-Z., Yin, X.-C. and Yu, X.-X. 2018. Characteristics and environmentally friendly extraction of cellulose nanofibrils from sugarcane bagasse. *Industrial Crops and Products*, 111: 285-291.

Fockink, D. H., Maceno, M. A. C. and Ramos, L. P. 2015. Production of cellulosic ethanol from cotton processing residues after pretreatment with dilute sodium hydroxide and enzymatic hydrolysis. *Bioresource Technology*, 187: 91–96.

Forero, J. A. J., Tran, T. H., Tana, T., Baker, A., Beltramini, J., Doherty, W. O. and Moghaddam, L. 2022. Hydrothermal liquefaction of sugarcane bagasse to bio-oils: effect of liquefaction solvents on bio-oil stability. *Fuel*, 312: 122793.

Formann, S., Hahn, A., Janke, L., Stinner, W., Sträuber, H., Logroño, W. and Nikolausz, M. 2020. Beyond sugar and ethanol production: value generation opportunities through sugarcane residues. *Frontiers in Energy Research*, 8: 579577.

Gagliano, A., Nocera, F., Bruno, M. and Cardillo, G. 2017. Development of an equilibrium-based model of gasification of biomass by Aspen Plus. *Energy Procedia*, 111: 1010-1019.

Galbe, M. and Zacchi, G. 2015. Pretreatment: The key to efficient utilization of lignocellulosic materials. *Biomass and Bioenergy*, 46: 70-78.

Gautam, N. and Chaurasia, A. 2020. Study on kinetics and bio-oil production from rice husk, rice straw, bamboo, sugarcane bagasse and neem bark in a fixed-bed pyrolysis process. *Energy*, 190: 116434.

Ge, X., Xu, F. and Li, Y. 2016. Solid-state anaerobic digestion of lignocellulosic biomass: recent progress and perspectives. *Bioresource Technology*, 205: 239-249.

Gheewala, S. H. 2023. Life cycle assessment for sustainability assessment of biofuels and bioproducts. *Biofuel Research Journal*, 10 (1): 1810-1815.

Giacomella, L. 2021. Techno-economic assessment (TEA) and life cycle costing analysis (LCCA): Discussing methodological steps and integrability. *Insights into Regional Development*, 3 (2): 176-197.

Globalpetrolprices. 2023. Available: https://www.globalpetrolprices.com/South-Africa/ (Accessed June/25/2024).

Golsteijn, L. *PRé Sustainability* (online). 2020. Available: https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/ (Accessed July/ 11/2023).

Gomez, E., Nogueira, D. W. O., Oliveira, E. A. D., de Souza, P. M. C. and dE Almeida, R. F. G. 2010. Gasification of sugarcane bagasse in a downdraft gasifier: theoretical and experimental investigation. *Biomass and Bioenergy*, 34 (8): 1207-1218.

Gopalakrishnan, B., Khanna, N. and Das, D. 2019. Dark-fermentative biohydrogen production. In: *Biohydrogen*. Elsevier, 79-122.

Gorensek, M. B., Shukre, R. and Chen, C.-C. 2019. Development of a thermophysical properties model for flowsheet simulation of biomass pyrolysis processes. *ACS Sustainable Chemistry & Engineering*, 7 (9): 9017-9027.

Greenfutureinnovations. 2023. *Bioethanol and co-generation plant*. Available: https://www.greenfutureinnovations.com/faqs.html (Accessed August/15/2023).

Grimaldi, M. P., Marques, M. P., Laluce, C., Cilli, E. M. and Sponchiado, S. R. P. 2015. Evaluation of lime and hydrothermal pretreatments for efficient enzymatic hydrolysis of raw sugarcane bagasse. *Biotechnology for Biofuels*, 205 (1): 1-14.

Gubicza, K., Nieves, I. U., Sagues, W. J., Barta, Z., Shanmugam, K. and Ingram, L. O. 2016. Techno-economic analysis of ethanol production from sugarcane bagasse using a Liquefaction plus Simultaneous Saccharification and co-Fermentation process. *Bioresource Technology*, 208: 42-48.

Gunes, K., Yaglikci, M. and Celiktas, M. S. 2022. Pressurized liquid hot water pretreatment and enzymatic hydrolysis of switchgrass aiming at the enhancement of fermentable sugars. *Biofuels*, 13 (3): 359-364.

Guo, F., Liang, S., Jia, X., Peng, K., Jiang, X. and Qian, L. 2020. One-step synthesis of biochar-supported potassium-iron catalyst for catalytic cracking of biomass pyrolysis tar. *International Journal of Hydrogen Energy*, 45 (33): 16398-16408.

Guvvala, H. M., Nityanand. 2021. Art of anaerobic digestion: An overview. *Research Journal of Chemistry and Environment*, 25 (8): 168-176.

Ha, J. H. and Lee, I.-G. 2020. Study of a method to effectively remove char byproduct generated from fast pyrolysis of lignocellulosic biomass in a bubbling fluidized bed reactor. *Processes*, 8 (11): 1407.

Haigh, K., Mandegari, M., Farzad, S., Dafal, A. and Görgens, J. 2020. A biorefinery approach to improve the sustainability of the South African sugar industry: An assessment of selected scenarios. In: *Opportunities for Biomass and Organic Waste Valorisation: Finding Alternative Solutions to Disposal in South Africa*. First edn. 47.

Hallenbeck, P. C. and Ghosh, D. 2009. Advances in fermentative biohydrogen production: the way forward? *Trends in Biotechnology*, 27 (5): 287-297.

Hasibuan, S. J. and Handriyani, R. 2023. Cash flow analysis as a planning and control tool in PT. Berma karya Bersama. *Jurnal Ekonomi*, 12 (01): 1666-1671.

Hassan, S. N., Douglas, P. L. and Croiset, E. 2007. Techno-economic study of CO2 capture from an existing cement plant using MEA scrubbing. *International Journal of Green Energy*, 4 (2): 197-220.

Hitam, C. and Jalil, A. 2020. A review on biohydrogen production through photo-fermentation of lignocellulosic biomass. In: *Biomass Conversion and Biorefinery*. London, United Kingdom: 8465–8483.

Hoang, A. T., Nižetić, S., Olcer, A. I., Ong, H. C., Chen, W.-H., Chong, C. T., Thomas, S., Bandh, S. A. and Nguyen, X. P. 2021a. Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications. *Energy Policy*, 154: 112322.

Hoang, A. T., Ong, H. C., Fattah, I. R., Chong, C. T., Cheng, C. K., Sakthivel, R. and Ok, Y. S. 2021b. Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability. *Fuel Processing Technology*, 223: 106997.

Hosseinzadeh-Bandbafha, H., Nizami, A.-S., Kalogirou, S. A., Gupta, V. K., Park, Y.-K., Fallahi, A., Sulaiman, A., Ranjbari, M., Rahnama, H. and Aghbashlo, M. 2022. Environmental life cycle assessment of biodiesel production from waste cooking oil: A systematic review. *Renewable and Sustainable Energy Reviews*, 161: 112411.

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B. and Worley, M. 2011. *Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Ibrahim, H. A.-H. 2020. Introductory chapter: pyrolysis. *Recent Advances in Pyrolysis*, 1.

IEABioenergy. 2023. *Biomass gasification and syngas production*
IEA Bioenergy.

IEABioenergyTask37. 2022. *Biogas upgrading to biomethane – Technology review*. IEA Bioenergy.

Ighalo, J. O., Iwuchukwu, F. U., Eyankware, O. E., Iwuozor, K. O., Olotu, K., Bright, O. C. and Igwegbe, C. A. 2022. Flash pyrolysis of biomass: a review of recent advances. *Clean Technologies and Environmental Policy*, 24 (8): 2349-2363.

IllovoSugarSouthAfrica. 2023. *Electricity Co-Generation*. Available: https://www.illovosugarafrica.com/our-brands/electricity-co-generating#:~:text=POWER%20GENERATION,crushed%20stalks%20of%20sugar%20cane. (Accessed July/06/2023).

Inayat, A., Ahmed, A., Tariq, R., Waris, A., Jamil, F., Ahmed, S. F., Ghenai, C. and Park, Y.-K. 2022. Techno-economical evaluation of bio-oil production via biomass fast pyrolysis process: a review. *Frontiers in Energy Research*, 9: 770355.

Inayat, A., Inayat, M., Shahbaz, M., Sulaiman, S. A., Raza, M. and Yusup, S. 2020. Parametric analysis and optimization for the catalytic air gasification of palm kernel shell using coal bottom ash as catalyst. *Renewable Energy*, 145: 671-681.

Issa, K., Salma, M., Saleh, Omer, Hanan, B. and Mousay, A. 2020. Recent Advances of Biogas Production and Future Perspective. In: *IntechOpen*. IntechOpen, 1-40.

Ivaniš, M., Filipović, L. and Ivaniš, M. 2021. Cash Flow analysis. In: Proceedings of *Engineering Management and Competitiveness 2021 (EMC 2021)*. 217.

Jarungthammachote, S. and Dutta, A. 2008. Equilibrium modeling of gasification: Gibbs free energy minimization approach and its application to spouted bed and spout-fluid bed gasifiers. *Energy Conversion and Management*, 49 (6): 1345-1356.

Jayathilaka, A. K. 2020. Operating profit and net profit: measurements of profitability. *Open Access Library Journal*, 7 (12): 1-11.

Jiang, P., Van Fan, Y. and Klemeš, J. J. 2021. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Applied Energy*, 285: 116441.

Jiang, Y., McAdam, E., Zhang, Y., Heaven, S., Banks, C. and Longhurst, P. 2019. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. *Journal of Water Process Engineering*, 32: 100899.

Joseph, A. M., Tulasi, Y., Shrivastava, D. and Kiran, B. 2023. Techno-economic feasibility and exergy analysis of bioethanol production from waste. *Energy Conversion and Management: X*, 18: 100358.

Kabeyi, M. J. B. and Olanrewaju, O. A. 2022. Technologies for biogas to electricity conversion. *Energy Reports*, 8: 774-786.

Kabeyi, M. J. B. and Olanrewaju, O. A. 2023. Bagasse Electricity Potential of Conventional Sugarcane Factories. *Journal of Energy*, 2023.

Kadwa, M. 2013. An overview of sugarcane supply chain inconsistencies. *School of Engineering, University of KwaZulu-Natal, PhD degree. Pietermaritzburg, South Africa*, Article ID.

Kalak, T. 2023. Potential Use of Industrial Biomass Waste as a Sustainable Energy Source in the Future. *Energies*, 16 (4): 1783.

Kamran, M. 2021. Chapter 8 - Bioenergy. In: Kamran, M. and Fazal, M. R. eds. *Renewable Energy Conversion Systems*. Academic Press, 243-264. Available: https://www.sciencedirect.com/science/article/pii/B9780128235386000026 (Accessed January/01/2022).

Kansha, Y., Abbas, A. and Manaf, N. A. 2024. Unlocking the techno-economic potential of biomass gasification for power generation: Comparative analysis across diverse plant capacities. *Waste Management*, 189: 219-229.

Kapanji, K. K., Haigh, K. F. and Görgens, J. F. 2021. Techno-economics of lignocellulose biorefineries at South African sugar mills using the biofine process to co-produce levulinic acid, furfural and electricity along with gamma valeractone. *Biomass and Bioenergy*, 146: 106008.

Karthikeyan, O. P. and Visvanathan, C. 2013. Bio-energy recovery from high-solid organic substrates by dry anaerobic bio-conversion processes: a review. *Reviews in Environmental Science and Bio/Technology*, 12: 257-284.

Kasavi, C., Finore, I. and Lama, L. 2015. Evaluation of industrial Saccharomyces cerevisiae strains for ethanol production from biomass. *Biomass- Bioenergy*, 45: 230-238.

Kasmuri, N., Kamarudin, S., Abdullah, S., Hasan, H. and Som, A. M. 2019. Integrated advanced nonlinear neural network-simulink control system for production of bio-methanol from sugar cane bagasse via pyrolysis. *Energy*, 168: 261-272.

Kaur, S. and Singh, A. 2021. Environmental Problems Related to Sugar Industries: A Case Study of Govind Sugar Mill Ltd, Aira, Lakhimpur Kheri,". *International Journal of Innovative Science and Research Technology*, 6 (9).

Kavitha, S., Banu, J. R., Arulazhagan, P. and Gunasekaran, M. 2020. Environmental impacts and sustainability assessment of food loss and waste valorization: Value chain analysis of food consumption. In: *Food Waste to Valuable Resources*. Elsevier, 359-388.

Kazi, F. K., Fortman, J., Anex, R., Kothandaraman, G., Hsu, D., Aden, A. and Dutta, A. 2010. *Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Kisiga, W. 2024. Techno-economic analysis and life cycle assessment for production of biofuels from spent coffee grounds. Master of Engineering, Durban University of Technology.

Kisiga, W., Chetty, M. and Rathilal, S. 2024. Environmental impact assessment of alternative technologies for production of biofuels from spent coffee grounds. *Energy Science & Engineering*, 12 (11): 4823-4842.

Kokare, S., Oliveira, J. and Godina, R. 2023. Life cycle assessment of additive manufacturing processes: A review. *Journal of Manufacturing Systems*, 68: 536-559.

Kombe, E. Y., Lang'at, N., Njogu, P., Malessa, R., Weber, C.-T., Njoka, F. and Krause, U. 2022. Numerical investigation of sugarcane bagasse gasification using Aspen Plus and response surface methodology. *Energy Conversion and Management*, 254: 115198.

Konde, K. S., Nagarajan, S., Kumar, V., Patil, S. V. and Ranade, V. V. 2021. Sugarcane bagasse based biorefineries in India: potential and challenges. *Sustainable Energy & Fuels*, 5 (1): 52-78.

Koul, B., Yakoob, M. and Shah, M. P. 2022. Agricultural waste management strategies for environmental sustainability. *Environmental Research*, 206: 112285.

Kovacs, E., Hoaghia, M.-A., Senila, L., Scurtu, D. A., Varaticeanu, C., Roman, C. and Dumitras, D. E. 2022. Life cycle assessment of biofuels production processes in viticulture in the context of circular economy. *Agronomy*, 12 (6): 1320.

Kulkarni, P. P., Khonde, V. K., Deshpande, M. S., Sabale, T. R., Kumbhar, P. S. and Ghosalkar, A. R. 2021. Selection of methanotrophic platform for methanol production using methane and biogas. *Journal of Bioscience and Bioengineering*, 132 (5): 460-468.

Kumar, A. and Beohar, G. 2022. A review on "bagasse direct combustion in boiler furnace at different parameters. *International Research Journal of Modernization in Engineering Technology and Science*, 04 (05): 1-4.

Kumar, A., Rapoport, A., Kunze, G., Kumar, S., Singh, D. and Singh, B. 2020. Multifarious pretreatment strategies for the lignocellulosic substrates for the generation of renewable and sustainable biofuels: A review. *Renewable Energy*, 160: 1228-1252.

Kumar, A. K. and Sharma, S. 2017a. Recent updates on different methods of pretreatment of lignocellulosic feedstocks. *Bioresouces and Bioprocessing*, 4 (7): 1-19.

Kumar, A. K. and Sharma, S. 2017b. Recent updates on different methods of pretreatment of lignocellulosic feedstocks: a review. *Bioresources and Bioprocessing*, 4 (1): 1-19.

Kumar, R. S., Singh, P. and Ghosh, S. 2022. Sequential fermentation for enhanced volumetric productivity of bioethanol from mixed sugars. *Fuel*, 308: 121984.

Kunz, A., Steinmetz, R. L. R. and do Amaral, A. C. 2022. *Fundamentals of anaerobic digestion, biogas purification, use and treatment of digestate*. 1st ed.

Labatut, R. A., Angenent, L. T. and Scott, N. R. 2014. Conventional mesophilic vs. thermophilic anaerobic digestion: a trade-off between performance and stability? *Water Research*, 53: 249-258.

Lachos-Perez, D., Martins-Vieira, J. C., Missau, J., Anshu, K., Siakpebru, O. K., Thengane, S. K., Morais, A. R. C., Tanabe, E. H. and Bertuol, D. A. 2023. Review on biomass pyrolysis with a focus on bio-oil upgrading techniques. *Analytica*, 4 (2): 182-205.

Lantz, M., Svensson, M., Björnsson, L. and Börjesson, P. 2007. The prospects for an expansion of biogas systems in Sweden—Incentives, barriers and potentials. *Energy Policy*, 35 (3): 1830-1843.

Lee, E., Bittencourt, P., Casimir, L., Jimenez, E., Wang, M., Zhang, Q. and Ergas, S. J. 2019. Biogas production from high solids anaerobic co-digestion of food waste, yard waste and waste activated sludge. *Waste Management*, 95: 432-439.

Lehmann, J., Abiven, S., Kleber, M., Pan, G., Singh, B. P., Sohi, S. P. and Zimmerman, A. R. 2015. Persistence of biochar in soil. In: *Biochar for environmental management*. Routledge, 235-282.

Leibbrandt, N. H. 2010. Techno-economic study for sugarcane bagasse to liquid biofuels in South Africa: a comparison between biological and thermochemical process routes. Doctoral Thesis, Stellenbosch University.

Li, G., Lu, Z., Zhang, J., Li, H., Zhou, Y., Zayan, A. M. I. and Huang, Z. 2020. Life cycle assessment of biofuel production from microalgae cultivated in anaerobic digested wastewater. *International Journal of Agricultural and Biological Engineering*, 13 (1): 241-246.

Li, X., Wang, Z., He, Y., Wang, Y., Wang, S., Zheng, Z., Wang, S., Xu, J., Cai, Y. and Ying, H. 2024. A Comprehensive Review of the Strategies to Improve Anaerobic Digestion: Their Mechanism and Digestion Performance. *Methane*, 3 (2): 227-256.

Lima, D. R. S., de Oliveira Paranhos, A. G., Adarme, O. F. H., Baêta, B. E. L., Gurgel, L. V. A., dos Santos, A. S., de Queiroz Silva, S. and de Aquino, S. F. 2022. Integrated production of second-generation ethanol and biogas from sugarcane bagasse pretreated with ozone. *Biomass Conversion and Biorefinery*, 12: 809–825.

Lin, C.-Y., Chu, C.-Y., Lay, C.-H. and Leu, H.-J. 2016. Fermentative hydrogen and methane productions from organic wastes: a review. *Current Biochemical Engineering*, 3 (1): 16-23.

Liu, H., Huang, Y., Yuan, H., Yin, X. and Wu, C. 2018. Life cycle assessment of biofuels in China: status and challenges. *Renewable and Sustainable Energy Reviews*, 97: 301-322.

Liu, Y., Yuan, Y., Ramya, G., Singh, S. M., Chi, N. T. L., Pugazhendhi, A., Xia, C. and Mathimani, T. 2022. A review on the promising fuel of the future–Biobutanol; the hindrances and future perspectives. *Fuel*, 327: 125166.

Logan, M. and Visvanathan, C. 2019. Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. *Waste Management & Research*, 37 (1_suppl): 27-39.

Loyte, A., Suryawanshi, J., Bhiogade, G., Devarajan, Y. and Subbiah, G. 2022. Recent developments in utilizing hydrous ethanol for diverse engine technologies. *Chemical Engineering and Processing-Process Intensification*, 177: 108985.

Luca, E., Chaplot, V., Mutema, M., Feller, C., Ferreira, M., Cerri, C. C. and Couto, H. T. Z. d. 2018. Effect of conversion from sugarcane preharvest burning to residues green-trashing on SOC stocks and soil fertility status: Results from different soil conditions in Brazil. *Geoderma*, 310: 238-248.

Lynd, L. R., Beckham, G. T., Guss, A. M., Jayakody, L. N., Karp, E. M., Maranas, C., McCormick, R. L., Amador-Noguez, D., Bomble, Y. J. and Davison, B. H. 2022. Toward low-cost biological and hybrid biological/catalytic conversion of cellulosic biomass to fuels. *Energy & Environmental Science*, 15 (3): 938-990.

Magrini, F. E., Castilhos, A., Lora, L. B. and Paesi, S. 2023. Strategies of co-cultures and bioaugmentation by Bacillus amyloliquefaciens, Clostridium bifermentans, Enterobacter muelleri, and E. tabaci for increasing the production of hydrogen from raw glycerol. *Biomass and Bioenergy*, 168: 106672.

Mahapatra, S., Kumar, D., Singh, B. and Sachan, P. K. 2021. Biofuels and their sources of production: A review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus. *Energy Nexus*, 4: 100036.

Makepa, D. C., Chihobo, C. H., Ruziwa, W. R. and Musademba, D. 2023. A systematic review of the techno-economic assessment and biomass supply chain uncertainties of biofuels production from fast pyrolysis of lignocellulosic biomass. *Fuel Communications*, 14: 100086.

Mandegari, M. A., Farzad, S. and Görgens, J. F. 2016. Self-Energy Sufficiency Assessment of the Biorefinery Annexed to a Typical

South African Sugar Mill. *International Journal of Energy and Power Engineering*, 10 (01): 1-2.

Mandegari, M. A., Farzad, S. and Görgens, J. F. 2017. Economic and environmental assessment of cellulosic ethanol production scenarios annexed to a typical sugar mill. *Bioresource Technology*, 224: 314-326.

Mandegari, M. A., Farzad, S., Van Rensburg, E. and Görgens, J. F. 2017. Multi-criteria analysis of a biorefinery for co-production of lactic acid and ethanol from sugarcane lignocellulose. *Biofuels, Bioproducts and Biorefining*, 11 (6): 971-990.

Mari Selvam, S., Balasubramanian, P., Chintala, M. and Gujjala, L. K. S. 2025. Techno-economic analysis of microwave pyrolysis of sugarcane bagasse biochar production. *Biomass Conversion and Biorefinery*, 15 (9): 14229-14239.

Martinez-Hernandez, E., Amezcua-Allieri, M. A., Sadhukhan, J. and Anell, J. A. 2018. Sugarcane bagasse valorization strategies for bioethanol and energy production. In: *Sugarcane-Technology and Research*. Centre for Environment and Sustainability, University of Surrey, Guildford, UK.

Mavukwana, A., Jalama, K., Ntuli, F. and Harding, K. 2013. Simulation of sugarcane bagasse gasification using aspen plus. In: Proceedings of *International Conference on Chemical and Environmental Engineering (ICCEE), Johannesburg, South Africa*. 70-74.

Maxwell, C. 2024. *Cost Indices*. Available: https://toweringskills.com/financial-analysis/cost-indices/ (Accessed 25 June 2024).

McAloon, A., Taylor, F., Yee, W., Ibsen, K. and Wooley, R. 2000. *Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Meegoda, J. N., Li, B., Patel, K. and Wang, L. B. 2018. A review of the processes, parameters, and optimization of anaerobic digestion. *International Journal of Environmental Research and Public Health*, 15 (10): 2224.

Mehta, J. M. and Brezinsky, K. 2023. *Natural gas for combustion systems*. Elsevier.

Meier, D. 2019. *Pyrolysis oil biorefinery*. Springer.

Meisam, T., HG. 2018. Biogas Fundamentals, Process and Operation. *Biofuel and Biorefinery Technologies*, 6: 1-230.

Miranda, N. T., Motta, I. L., Maciel Filho, R. and Maciel, M. R. W. 2021. Sugarcane bagasse pyrolysis: A review of operating conditions and products properties. *Renewable and Sustainable Energy Reviews*, 149: 111394.

Mohajan, H. 2011. Greenhouse gas emissions increase global warming. 1 (2): 21-34.

Mohammadi, A. and Anukam, A. 2022. *The technical challenges of the gasification technologies currently in use and ways of optimizing them: a review*. intechopen.

Mohammadi, F., Roedl, A., Abdoli, M. A., Amidpour, M. and Vahidi, H. 2020. Life cycle assessment (LCA) of the energetic use of bagasse in Iranian sugar industry. *Renewable Energy*, 145: 1870-1882.

Mohanty, A., Ajmera, S., Chinnam, S., Kumar, V., Mishra, R. K. and Acharya, B. 2024. Pyrolysis of waste oils for biofuel production: An economic and life cycle assessment. *Fuel Communications*, 18: 100108.

Montgomery, D. C. 2019. *Introduction to statistical quality control*. John wiley & sons.

Moonsamy, T. A. 2021. Techno-economic analysis and benchmarking of integrated first and second generation biorefinery scenarios annexed to a typical sugar mill for bioethanol production. Master of Engineering, Stellenbosch University.

Morales, H., di Sciascio, F., Aguirre-Zapata, E. and Amicarelli, A. 2024. Crystallization process in the sugar industry: a discussion on fundamentals, industrial practices, modeling, estimation and control. *Food Engineering Reviews*, 16 (3): 441-469.

Moussa, R. N., Moussa, N. and Dionisi, D. 2022. Hydrogen production from biomass and organic waste using dark fermentation: an analysis of literature data on the effect of operating parameters on process performance. *Processes*, 10 (1): 156.

Mukwevho, M. J., Maharajh, D. and Chirwa, E. M. N. 2020. Evaluating the effect of ph, temperature, and hydraulic retention time on biological sulphate reduction using response surface methodology. *Water*, 12 (10): 2662.

Munagala, M., Shastri, Y., Nalawade, K., Konde, K. and Patil, S. 2021. Life cycle and economic assessment of sugarcane bagasse valorization to lactic acid. *Waste Management*, 126: 52-64.

Murali, G. and Shastri, Y. 2019. Life-cycle assessment-based comparison of different lignocellulosic ethanol production routes. *Biofuels*, 13 (2): 237-247.

Mussatto, S. I., Dragone, G., Guimarães, P. M., Silva, J. P. A., Carneiro, L. M., Roberto, I. C., Vicente, A., Domingues, L. and Teixeira, J. A. 2010. Technological trends, global market, and challenges of bio-ethanol production. *Biotechnology Advances*, 28 (6): 817-830.

Nahak, B., Preetam, S., Sharma, D., Shukla, S., Syväjärvi, M., Toncu, D.-C. and Tiwari, A. 2022. Advancements in net-zero pertinency of lignocellulosic biomass for climate neutral energy production. *Renewable and Sustainable Energy Reviews*, 161: 112393.

Nakasu, P., Ienczak, J., Rabelo, S. and Costa, A. 2021. The water consumption of sugarcane bagasse post-washing after protic ionic liquid pretreatment and its impact on 2G ethanol production. *Industrial Crops and Products*, 169: 113642.

Nallasivam, J., Prashanth, P. F. and Vinu, R. 2022. *Hydrothermal liquefaction of biomass for the generation of value-added products*. Elsevier.

Narisetty, V., Cox, R., Bommareddy, R., Agrawal, D., Ahmad, E., Pant, K. K., Chandel, A. K., Bhatia, S. K., Kumar, D. and Binod, P. 2022. Valorisation of xylose to renewable fuels and chemicals, an essential step in augmenting the commercial viability of lignocellulosic biorefineries. *Sustainable Energy & Fuels*, 6 (1): 29-65.

Naseeruddin, S., Desai, S. and Venkateswar Rao, L. 2021. Co-culture of Saccharomyces cerevisiae (VS3) and Pichia stipitis (NCIM 3498) enhances bioethanol yield from concentrated Prosopis juliflora hydrolysate. *3 Biotech*, 11 (1): 21.

Ngan, N. V. C., Chan, F. M. S., Nam, T. S., Thao, H. V., Maguyon-Detras, M. C., Hung, D. V., Cuong, D. M. and Hung, N. V. 2020. Anaerobic Digestion of Rice Straw. In: *Sustainable Rice Straw Management*. 56-92.

Nkoa, R. 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agronomy for Sustainable Development*, 34 (2): 473-492.

Nogueira, L. A. H., Kang, S. and Skeer, J. 2019. *Economic potential for sustianable scale-up*. Abu Dhabi: International Renewable Energy Agency.

Nosratpour, M. J., Karimi, K. and Sadeghi, M. 2018. Improvement of ethanol and biogas production from sugarcane bagasse using sodium alkaline pretreatments. *Journal of Environmental Management*, 226: 329-339.

Ntimbani, R. N., Farzad, S. and Görgens, J. F. 2021. Techno-economic assessment of one-stage furfural and cellulosic ethanol co-production from sugarcane bagasse and harvest residues feedstock mixture. *Industrial Crops and Products*, 162: 113272.

O'Hara, I. and Mundree, S. 2016. *Sugarcane-based biofuels and bioproducts*. John Wiley & Sons.

Omolayo, Y., Feingold, B. J., Neff, R. A. and Romeiko, X. X. 2021. Life cycle assessment of food loss and waste in the food supply chain. *Resources, Conservation and Recycling*, 164: 105119.

Onthong, U. and Juntarachat, N. 2017. Evaluation of biogas production from raw and processed agricultural wastes. *Energy Procedia*, 138: 205-210.

Ordonez-Loza, J., Chejne, F., Jameel, A. G. A., Telalovic, S., Arrieta, A. A. and Sarathy, S. M. 2021. An investigation into the pyrolysis and oxidation of bio-oil from sugarcane bagasse: Kinetics and evolved gases using TGA-FTIR. *Journal of Environmental Chemical Engineering*, 9 (5): 106144.

Ortiz, P. A. S., Marechal, F. and de Oliveira Junior, S. 2020. Exergy assessment and techno-economic optimization of bioethanol production routes. *Fuel*, 279: 118327.

Paixão, S. M., Ladeirab, S. A., Silvaa, T. P., Areza, B. F., Roseiroa, J. C. and Martinsb, M. L. L. 2016. Sugarcane bagasse delignification with potassium hydroxide for enhanced enzymatic hydrolysis. *RSC Advances*, 6: 1042-1052.

Pan, S., Zabed, H. M., Wei, Y. and Qi, X. 2022. Technoeconomic and environmental perspectives of biofuel production from sugarcane bagasse: Current status, challenges and future outlook. *Industrial Crops and Products*, 188: 115684.

Paolini, V., Tratzi, P., Torre, M., Tomassetti, L., Segreto, M. and Petracchini, F. 2021. *Water scrubbing for biogas upgrading: developments and innovations*. Elsevier

Parajuli, A., Khadka, A., Sapkota, L. and Ghimire, A. 2022. Effect of hydraulic retention time and organic-loading rate on two-staged, semi-continuous mesophilic anaerobic digestion of food waste during start-up. *Fermentation*, 8 (11): 620.

Parvari, E., Mahajan, D. and Hewitt, E. L. 2025. A review of biomass pyrolysis for production of fuels: Chemistry, processing, and techno-economic analysis. *Biomass*, 5 (3): 54.

Parvez, Y. and Kumar, R. 2022. Exergy Based Performance Improvement of Cogeneration Plant of Sugar Mills. Article ID.

Patel, M., Zhang, X. and Kumar, A. 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. *Renewable and Sustainable Energy Reviews*, 53: 1486-1499.

Patel, R., Rajaraman, T., Rana, P., Ambegaonkar, N. and Patel, S. 2025. A review on techno-economic analysis of lignocellulosic biorefinery producing biofuels and high-value products. *Results in Chemistry*, Article ID: 102052.

Pati, S., De, S. and Chowdhury, R. 2023. Exploring the hybrid route of bio-ethanol production via biomass co-gasification and syngas fermentation from wheat straw and sugarcane bagasse: model development and multi-objective optimization. *Journal of Cleaner Production*, 395: 136441.

Payscale. 2024. *Average Operator Pay in South Africa*. Available: https://www.payscale.com/research/ZA/Job=A-Operator/Hourly_Rate (Accessed 25 June 2024).

Pearce, J. M. and Parncutt, R. 2023. Quantifying Global Greenhouse Gas Emissions in Human Deaths to Guide Energy Policy. *Energies*, 16 (16): 6074.

Pereira, S. C., Maehara, L., Machado, C. M. M. and Farinas, C. S. 2015. 2G ethanol from the whole sugarcane lignocellulosic biomass. *Biotechnology for Biofuels*, 8 (1): 1-16.

Periyasamy, S., Isabel, J. B., Kavitha, S., Karthik, V., Mohamed, B. A., Gizaw, D. G., Sivashanmugam, P. and Aminabhavi, T. M. 2023. Recent advances in consolidated bioprocessing for conversion of lignocellulosic biomass into bioethanol–A review. *Chemical Engineering Journal*, 453: 139783.

Petersen, A. M. 2012. *Comparisons of the technical, financial risk, and life cycle assessments of various sugarcane bagasse processing options to biofuels in South Africa*. Stellenbosch: Stellenbosch University.

Petersson, A., & Wellinger, A. 2009. *Biogas upgrading technologies – Developments and innovations*.

Pinheiro Pires, A. P., Arauzo, J., Fonts, I., Domine, M. E., Fernandez Arroyo, A., Garcia-Perez, M. E., Montoya, J., Chejne, F., Pfromm, P. and Garcia-Perez, M. 2019. Challenges and opportunities for bio-oil refining: A review. *Energy & Fuels*, 33 (6): 4683-4720.

Pino, M. S., Rodríguez-Jasso, R. M., Michelin, M., Flores-Gallegos, A. C., Morales-Rodriguez, R., Teixeira, J. A. and Ruiz, H. A. 2018. Bioreactor design for enzymatic hydrolysis of biomass under the biorefinery concept. *Chemical Engineering Journal*, 347: 119-136.

Pippo, W. A., Luengo, C. A., Alberteris, L. A., Pino, G. G. and Neto, J. E. 2014. Energy Recovery from Sugarcane: Study of Heating Value Variations of Sugarcane-trash with Moisture Content during the Milling Season. *American Journal of Biomass and Bioenergy*, 3 (3): 1-33.

Poddar, B., Nakhate, S., Gupta, R., Chavan, A., Singh, A., Khardenavis, A. and Purohit, H. 2022. A comprehensive review on the pretreatment of lignocellulosic wastes for improved biogas production by anaerobic digestion. *International Journal of Environmental Science and Technology*, 19: 3429–3456.

PowerAfrica. 2023. *South Africa - Country Commercial Guide*. Available: https://www.trade.gov/country-commercial-guides/south-africa-energy#:~:text=South%20Africa%20Integrated%20Resource%20Plan%20(IRP)&text=The%20NDP%20lays%20out%20a,Integrated%20Resource%20Plan%20(IRP). (Accessed July/06/2023).

Prabhu, A. V., Sivaram, A., Prabhu, N. and Sundaramahalingam, A. 2021. A study of enhancing the biogas production in anaerobic digestion. *Materials Today: Proceedings*, 45: 7994-7999.

Rabelo, S. C., Filho, R. M. F. and Costa, A. C. 2009. Lime pretreatment of sugarcane bagasse for bioethanol production. *Applied Biochemistry and Biotechnology*, 153: 139-150.

Rabemanolontsoa, H. and Saka, S. 2016. Various pretreatments of lignocellulosics. *Bioresource Technology*, 199: 83-91.

Rafiee, A., Khalilpour, K. R., Prest, J. and Skryabin, I. 2021. Biogas as an energy vector. *Biomass and Bioenergy*, 144: 105935.

Raj, T., Chandrasekhar, K., Kumar, A. N., Banu, J. R., Yoon, J.-J., Bhatia, S. K., Yang, Y.-H., Varjani, S. and Kim, S.-H. 2022. Recent advances in commercial biorefineries for lignocellulosic ethanol production: Current status, challenges and future perspectives. *Bioresource Technology*, 344: 126292.

Ramirez, J. A., Brown, R. and Rainey, T. J. 2018. Techno-economic analysis of the thermal liquefaction of sugarcane bagasse in ethanol to produce liquid fuels. *Applied Energy*, 224: 184-193.

Ramirez, J. A. and Rainey, T. J. 2019. Comparative techno-economic analysis of biofuel production through gasification, thermal liquefaction and pyrolysis of sugarcane bagasse. *Journal of Cleaner Production*, 229: 513-527.

Rao, R. N., Silitonga, A. S., Shamsuddin, A. H., Milano, J., Riayatsyah, T. M. I., Sebayang, A., Nur, T. B., Sabri, M., Yulita, M. and Sembiring, R. 2020. Effect of ethanol and gasoline blending on the performance of a stationary small single cylinder engine. *Arabian Journal for Science and Engineering*, 45: 5793-5802.

Raveendran, K., Ganesh, A. and Khilar, K. C. 1995. Influence of mineral matter on biomass pyrolysis characteristics. *Fuel*, 74 (12): 1812-1822.

Ravendran, R., Abdulrazik, A. and Zailan, R. 2019a. Aspen Plus simulation of optimal biogas production in anaerobic digestion process. *IOP Conference Series: Materials Science and Engineering*, 702 (1): 012001.

Ravendran, R., Abdulrazik, A. and Zailan, R. 2019b. Aspen Plus simulation of optimal biogas production in anaerobic digestion process. In: Proceedings of *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 012001.

Rech, F. R., Fontana, R. C., Rosa, C. A., Camassola, M., Ayub, M. A. Z. and Dillon, A. J. 2019. Fermentation of hexoses and pentoses from sugarcane bagasse hydrolysates into ethanol by Spathaspora hagerdaliae. *Bioprocess and Biosystems Engineering*, 42: 83-92.

Reis, C. E. R., Junior, N. L., Bento, H. B., de Carvalho, A. K. F., de Souza Vandenberghe, L. P., Soccol, C. R., Aminabhavi, T. M. and Chandel, A. K. 2023. Process strategies to reduce cellulase enzyme loading for renewable sugar production in biorefineries. *Chemical Engineering Journal*, 451: 138690.

Ripple, W. J., Wolf, C., Newsome, T. M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M. I., Laurance, W. F. and 15, S. S. f. C. 2017. World scientists' warning to humanity: a second notice. *BioScience*, 67 (12): 1026-1028.

Riya, S., Meng, L., Wang, Y., Lee, C. G., Zhou, S., Toyota, K. and Hosomi, M. 2020. Dry anaerobic digestion for agricultural waste recycling. In: *Biogas-Recent Advances and Integrated Approaches*. IntechOpen, 43.

Riya, S., Suzuki, K., Meng, L., Zhou, S., Terada, A. and Hosomi, M. 2018. The influence of the total solid content on the stability of dry-thermophilic anaerobic digestion of rice straw and pig manure. *Waste Management*, 76: 350-356.

Ruchala, J. and Sibirny, A. A. 2021. Pentose metabolism and conversion to biofuels and high-value chemicals in yeasts. *FEMS Microbiology Reviews*, 45 (4): fuaa069.

Sabiha-Hanim, S. and Halim, N. A. A. 2018. Sugarcane bagasse pretreatment methods for ethanol production. In. Shah Alam: IntechOpen, 63-80.

Sadare, O. O., Ejekwu, O., Moshokoa, M. F., Jimoh, M. O. and Daramola, M. O. 2021. Membrane purification techniques for recovery of succinic acid obtained from fermentation broth during bioconversion of lignocellulosic biomass: Current advances and future perspectives. *Sustainability*, 13 (12): 6794.

Sahu, O. 2018. Assessment of sugarcane industry: Suitability for production, consumption, and utilization. *Annals of Agrarian Science*, 16 (4): 389-395.

Salinas, C. T., Pu, Y., Lou, C. and dos Santos, D. B. 2020. Experiments for combustion temperature measurements in a sugarcane bagasse large-scale boiler furnace. *Applied Thermal Engineering*, 175: 115433.

Sanadi, M. A. G. and Khot, S. A. 2024. Design & analysis of multiple effect evaporator for sugar industry. Article ID.

Sanchez-Borrego, F. J., Alvarez-Mateos, P. and Garcia-Martin, J. F. 2021. Biodiesel and other value-added products from bio-oil obtained from agrifood waste. *Processes*, 9 (5): 797.

Sanchez, O. J. and Cardona, C. A. 2008. Trends in biotechnological production of fuel ethanol from different feedstocks. *Bioresource Technology*, 99 (13): 5270-5295.

Santoyo-Castelazo, E., Santoyo, E., Zurita-García, L., Luengas, D. C. and Solano-Olivares, K. 2023. Life cycle assessment of bioethanol production from sugarcane bagasse using a gasification conversion process: bibliometric analysis, systematic literature review and a case study. *Applied Thermal Engineering*, 219: 119414.

Sapmaz, T., Mahboubi, A., Taher, M. N., Beler-Baykal, B., Karagunduz, A., Taherzadeh, M. J. and Koseoglu-Imer, D. Y. 2022. Waste-derived volatile fatty acid production and ammonium removal from it by ion exchange process with natural zeolite. *Bioengineered*, 13 (6): 14751-14769.

Saraeian, A., Nolte, M. W. and Shanks, B. H. 2019. Deoxygenation of biomass pyrolysis vapors: Improving clarity on the fate of carbon. *Renewable and Sustainable Energy Reviews*, 104: 262-280.

Sarker, S., Lamb, J. J., Hjelme, D. R. and Lien, K. M. 2019. A review of the role of critical parameters in the design and operation of biogas production plants. *Applied Sciences*, 9 (9): 1915.

SASA. 2021. *Cane Growing In South Africa*. Available: https://sasa.org.za/cane-growing-in-south-africa/ (Accessed July/01/2021).

SAshares.co.za. 2024. *Oil Prices*. Available: https://sashares.co.za/crude-oil-price/#gs.fuae2i (Accessed 23 August 2024).

Sathendra, E. R., Praveenkumar, R., Gurunathan, B., Chozhavendhan, S. and Jayakumar, M. 2022. Refining lignocellulose of second-generation biomass waste for bioethanol production. In: *Biofuels and Bioenergy*. Elsevier, 87-110.

Sharief, M., Mohamed, Y. and Saad, O. 2022. The Parameters Affecting the Process of Sugar Drying-Assalaya Sugar Factory-Sudan. *Journal of Engineering Studies and Computer science*, 1 (1): 49–56-49–56.

Sharma, S., Nair, A. and Sarma, S. J. 2021. Biorefinery concept of simultaneous saccharification and co-fermentation: Challenges and improvements. *Chemical Engineering and Processing-Process Intensification*, 169: 108634.

Sharma, S., Swain, M. R., Mishra, A., Mathur, A. S., Gupta, R. P., Puri, S. K., Ramakumar, S. and Sharma, A. K. 2021. High solid loading and multiple-fed simultaneous saccharification and co-fermentation (mf-SSCF) of rice straw for high titer ethanol production at low cost. *Renewable Energy*, 179: 1915-1924.

Shields, G. E. and Elvidge, J. 2020. Challenges in synthesising cost-effectiveness estimates. *Systematic Reviews*, 9 (1): 289.

Show, K.-Y., Lee, D.-J. and Chang, J.-S. 2011. Bioreactor and process design for biohydrogen production. *Bioresource Technology*, 102 (18): 8524-8533.

Show, K., Lee, D., Tay, J., Lin, C. and Chang, J. S. 2012. Biohydrogen production: current perspectives and the way forward. *International Journal of Hydrogen Energy*, 37 (20): 15616-15631.

Shukla, A. and Kumar, S. Y. 2017. A comparative study of sugarcane bagasse gasification and direct combustion. *Int. J. Appl. Eng. Res*, 12: 14739-14745.

Silva Ortiz, P. A., Maciel Filho, R. and Posada, J. 2019. Mass and heat integration in ethanol production mills for enhanced process efficiency and exergy-based renewability performance. *Processes*, 7 (10): 670.

Silveira, M. H. L., Morais, A. R. C., Da Costa Lopes, A. M., Olekszyszen, D. N. and Bogel-Łukasik, R. 2015. Current pretreatment technologies for the development of cellulosic. *ChemSusChem*, 8 (20): 3366-3390.

Sindhu, R., Binod, P., Pandey, A., Ankaram, S., Duan, Y. and Awasthi, M. K. 2019. Biofuel Production from Biomass:Toward Sustainable Development. In: *Current Development in Biotechnology and Bioengineering*. Elsevier, 79-92.

Sindhu, R., Binod, P., Pandey, A. and Gnansounou, E. 2020. Refining Biomass Residues for Sustainable Energy and Bioproducts. *Agroresidue-based Biorefineries*, 127: 243-258.

Singal, S. K., Goel, V., Nautiyal, H. and Papantonis, D. 2023. *Small Hydropower: Design and Analysis*. Elsevier.

Singh, N., Singhania, R. R., Nigam, P. S., Dong, C.-D., Patel, A. K. and Puri, M. 2022. Global status of lignocellulosic biorefinery: Challenges and perspectives. *Bioresource Technology*, 344: 126415.

Sirohi, R., Choi, H. I. and Sim, S. J. 2022. Microalgal fuels: Promising energy reserves for the future. *Fuel*, 312: 122841.

Sitotaw, Y. W., Habtu, N. G., Gebreyohannes, A. Y., Nunes, S. P. and Van Gerven, T. 2021. Ball milling as an important pretreatment technique in lignocellulose biorefineries: a review. *Biomass Conversion and Biorefinery*, 13: 5593–15616.

Siwal, S. S., Sheoran, K., Saini, A. K., Vo, D.-V. N., Wang, Q. and Thakur, V. K. 2022. Advanced thermochemical conversion technologies used for energy generation: Advancement and prospects. *Fuel*, 321: 124107.

Song, C., Zhang, C., Zhang, S., Lin, H., Kim, Y., Ramakrishnan, M., Du, Y., Zhang, Y., Zheng, H. and Barceló, D. 2020. Thermochemical liquefaction of agricultural and forestry wastes into biofuels and chemicals from circular economy perspectives. *Science of the Total Environment*, 749: 141972.

Srinadh, R. V. and Neelancherry, R. 2023. Technoeconomic and Sustainability Analysis of Agricultural Waste Conversion Technologies. In: *Agricultural Waste to Value-Added Products: Technical, Economic and Sustainable Aspects*. Springer, 47-68.

Srivastava, R. K., Shetti, N. P., Reddy, K. R., Kwon, E. E., Nadagouda, M. N. and Aminabhavi, T. M. 2021. Biomass utilization and production of biofuels from carbon neutral materials. *Environmental Pollution*, 276: 116731.

Stambuk, B. U., Alves Jr, L., Fongaro, G. and Müller, C. 2019. Yeasts: The leading figures on bioethanol production. In: *Ethanol as a Green Alternative Fuel: Insight and Perspectives*. 1st edn. New York:: Nova Science Publishers., 57-91.

Stančin, H., Mikulčić, H., Wang, X. and Duić, N. 2020. A review on alternative fuels in future energy system. *Renewable and Sustainable Energy Reviews*, 128: 109927.

Steffen, B., Egli, F., Pahle, M. and Schmidt, T. S. 2020. Navigating the clean energy transition in the COVID-19 crisis. *Joule*, 4 (6): 1137-1141.

Straathof, A. J. 2014. Transformation of biomass into commodity chemicals using enzymes or cells. *Chemical Reviews*, 114 (3): 1871-1908.

Sun, X., Atiyeh, H. K., Kumar, A. and Zhang, H. 2018. Enhanced ethanol production by Clostridium ragsdalei from syngas by incorporating biochar in the fermentation medium. *Bioresource Technology*, 247: 291-301.

Swanson, R. M., Platon, A., Satrio, J. A. and Brown, R. C. 2010. Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel*, 89: S11-S19.

Talukdar, D., Verma, D. K., Malik, K., Mohapatra, B. and Yulianto, R. 2017. Sugarcane as a Potential Biofuel Crop. In: *Sugarcane Biotechnology :Challenges and Prospects*. Kharagpur: Springer International Publishing, 123-137.

Tangney, P. 2020. Understanding climate change as risk: a review of IPCC guidance for decision-making. *Journal of Risk Research*, 23 (11): 1424-1439.

Teferra, D. M. and Wubu, W. 2018. Biogas for clean energy. In: *Anaerobic Digestion*. IntechOpen.

Teixeira, P., Bacariza, C., Correia, P., Pinheiro, C. I. and Cabrita, I. 2022. Hydrogen Production with In Situ CO2 Capture at High and Medium Temperatures Using Solid Sorbents. *Energies*, 15 (11): 4039.

Tezer, Ö., Karabağ, N., Öngen, A., Çolpan, C. Ö. and Ayol, A. 2022. Biomass gasification for sustainable energy production: A review. *International Journal of Hydrogen Energy*, 47 (34): 15419-15433.

Thoppil, Y. and Zein, S. H. 2021. Techno-economic analysis and feasibility of industrial-scale biodiesel production from spent coffee grounds. *Journal of Cleaner Production*, 307: 127113.

Tian, Z., Mohan, G. R., Ingram, L. and Pullammanappallil, P. 2013. Anaerobic digestion for treatment of stillage from cellulosic bioethanol production. *Bioresource Technology*, 144: 387-395.

Tiwari, B. R., Rouissi, T., Brar, S. K. and Surampalli, R. Y. 2021. Critical insights into psychrophilic anaerobic digestion: Novel strategies for improving biogas production. *Waste Management*, 131: 513-526.

Tofighi, A., Assadi, M. M., Asadirad, M. H. A. and Karizi, S. Z. 2014. Bio-ethanol production by a novel autochthonous thermo-tolerant yeast isolated from wastewater. *J. Environ. Health Sci. Eng*, 12 (107).

Tomlin, A. S. 2021. Air quality and climate impacts of biomass use as an energy source: A review. *Energy & Fuels*, 35 (18): 14213-14240.

Towler, G. and Sinnott, R. 2021. *Chemical engineering design: principles, practice and economics of plant and process design*. Butterworth-Heinemann.

TradingEconomics. 2024. *Ethanol commodity prices*. Available: https://tradingeconomics.com/commodity/ethanol (Accessed

Treichel, H. and Fongaro, G. 2019. *Improving biogas production: Technological challenges, alternative sources, future developments*. Cham: Springer.

Tsai, T.-Y., Lo, Y.-C., Dong, C.-D., Nagarajan, D., Chang, J.-S. and Lee, D.-J. 2020. Biobutanol production from lignocellulosic biomass using immobilized Clostridium acetobutylicum. *Applied Energy*, 277: 115531.

Tse, T. J., Wiens, D. J. and Reaney, M. J. 2021. Production of bioethanol—A review of factors affecting ethanol yield. *Fermentation*, 7 (4): 268.

Twidell, J. 2021. *Renewable energy resources*. Routledge.

Uellendahl, H. and Ahring, B. K. 2010. Anaerobic digestion as final step of a cellulosic ethanol biorefinery: Biogas production from fermentation effluent in a UASB reactor—pilot-scale results. *Biotechnology and Bioengineering*, 107 (1): 59-64.

Ummalyma, S. B., Sirohi, R., Udayan, A., Yadav, P., Raj, A., Sim, S. J. and Pandey, A. 2022. Sustainable microalgal biomass production in food industry wastewater for low-cost biorefinery products: a review. *Phytochemistry Reviews*, 22: 969–991.

Valladares-Diestra, K. K., de Souza Vandenberghe, L. P., Torres, L. A. Z., Nishida, V. S., Zandoná Filho, A., Woiciechowski, A. L. and Soccol, C. R. 2021. Imidazole green solvent pre-treatment as a strategy for second-generation bioethanol production from sugarcane bagasse. *Chemical Engineering Journal*, 420: 127708.

Vasconcelos, M. H., Mendes, F. M., Ramos, L., Dias, M. O. S., Bonomi, A., Jesus, C. D. F., Watanabe, M. D. B., Junqueira, T. L. and Milagres, A. M. F. 2020. Techno-economic assessment of bioenergy and biofuel production in integrated sugarcane biorefinery: Identification of technological. *Energy*, 199: 1-12.

Veiga, J. P. S. and Romanelli, T. L. 2020. Mitigation of greenhouse gas emissions using exergy. *Journal of Cleaner Production*, 260: 121092.

Veluswamy, G., Shah, K., Ball, A., Guwy, A. and Dinsdale, R. 2021. A techno-economic case for volatile fatty acid production for increased sustainability in the wastewater treatment industry. *Environmental Science: Water Research & Technology*, 7 (5): 927-941.

Vögeli, Y., Lohri, C. R., Gallardo, A., Diener, S. and Zurbrügg, C. 2014. Anaerobic digestion of biowaste in developing countries. *Swiss Federal Institute of Aquatic Science and Technology*, 137.

Voldsund, M., Jordal, K. and Anantharaman, R. 2016. Hydrogen production with CO2 capture. *International Journal of Hydrogen Energy*, 41 (9): 4969-4992.

Wagle, A., Angove, M. J., Mahara, A., Wagle, A., Mainali, B., Martins, M., Goldbeck, R. and Paudel, S. R. 2022. Multi-stage pre-treatment of lignocellulosic biomass for multi-product biorefinery: A review. *Sustainable Energy Technologies and Assessments*, 49: 101702.

Wang, H., Cao, L., Li, Q., Wijayawardene, N. N., Zhao, J., Cheng, M., Li, Q.-R., Li, X., Promputtha, I. and Kang, Y.-Q. 2022. Overexpressing GRE3 in Saccharomyces cerevisiae enables high ethanol production from different lignocellulose hydrolysates. *Frontiers in Microbiology*, 13: 1085114.

Wang, Z., Dien, B. S., Rausch, K. D., Tumbleson, M. and Singh, V. 2019. Improving ethanol yields with deacetylated and two-stage pretreated corn stover and sugarcane bagasse by

blending commercial xylose-fermenting and wild type Saccharomyces yeast. *Bioresource Technology*, 282: 103-109.

Wang, Z., Hu, Y., Wang, S., Wu, G. and Zhan, X. 2023. A critical review on dry anaerobic digestion of organic waste: Characteristics, operational conditions, and improvement strategies. *Renewable and Sustainable Energy Reviews*, 176: 113208.

Wang, Z., Wu, G. and Jönsson, L. J. 2018. Effects of impregnation of softwood with sulfuric acid and sulfur dioxide on chemical and physical characteristics, enzymatic digestibility, and fermentability. *Bioresource Technology*, 247: 200-208.

Weng, C., Peng, X. and Han, Y. 2021. Depolymerization and conversion of lignin to value-added bioproducts by microbial and enzymatic catalysis. *Biotechnology for Biofuels*, 14 (1): 1-22.

Wieck, T., Bennett, J. M., Redmond, T. and Young, A. 2019. Pressurised dewatering of sugarcane press mud for logistical transport efficiency and industrial reuse. *Sugar Tech*, 21: 235-243.

WorldBiocharFoundation. 2024. *Biochar market report.*
. World Biochar Foundation.

Wright, M. M., Daugaard, D. E., Satrio, J. A. and Brown, R. C. 2010. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *Fuel*, 89: S2-S10.

Wu, N. 2018. Techno-Economic Analysis of Biofuels Production. Doctorate (Ph.D.), University of Florida. Available: https://ufdc.ufl.edu/UFE0051799/00001 (Accessed 01/09/2021).

Wu, N., Moreira, C. M., Zhang, Y., Doan, N., Yang, S., Phlips, E. J., Svoronos, S. A. and Pullammanappallil, P. C. 2019a. Techno-economic analysis of biogas production from microalgae through anaerobic digestion. In: *Anaerobic Digestion*. IntechOpen, 113-146.

Wu, P., Li, J., He, T. and Hu, C. 2019b. The direct conversion of hemicelluloses to selectively produce xylose from corn stover catalysed by maleic acid. *BioResources*, 14 (1): 816-841.

Wunna, K., Nakasaki, K., Auresenia, J. L., Abella, L. C. and Gaspillo, P. D. 2017. Effect of alkali pretreatment on removal of lignin from sugarcane bagasse. *Chemical Engineering Transactions*, 56: 1831-1836.

Xiong, Y., Zhou, J., Xing, Z. and Du, K. 2020. Optimization of a volatile organic compound control strategy in an oil industry center in Canada by evaluating ozone and secondary organic aerosol formation potential. *Environmental Research*, 191: 110217.

Xu, C., Zhang, J., Zhang, Y., Guo, Y., Xu, H., Liang, C., Wang, Z. and Xu, J. 2019. Lignin prepared from different alkaline pretreated sugarcane bagasse and its effect on enzymatic hydrolysis. *International Journal of Biological Macromolecules*, 141: 484-492.

Yang, P., Columbus, E., Wooten, J., Batchelor, W., Buchireddy, P., Ye, X. and Wei, L. 2009. Evaluation of syngas storage under different pressures and temperatures. *Applied Engineering in Agriculture*, 25 (1): 121-128.

Ye, G., Zeng, D., Zhang, S., Fan, M., Zhang, H. and Xie, J. 2018. Ethanol production from mixtures of sugarcane bagasse and Dioscorea composita extracted residue with high solid loading. *Bioresource Technology*, 257: 23-29.

Yoro, K. O. and Daramola, M. O. 2020. CO2 emission sources, greenhouse gases, and the global warming effect. In: *Advances in carbon capture*. Elsevier, 3-28.

Yu, N., Tan, L., Sun, Z. Y., Nishimura, H., Takei, S. and Tang, Y. Q. 2018. Bioethanol from sugarcane bagasse:Focused on optimum of lignin content and reduction of enzyme addition. *Waste Management*, 76: 404-413.

Yu, Y., Wu, J., Ren, X., Lau, A., Rezaei, H., Takada, M., Bi, X. and Sokhansanj, S. 2022. Steam explosion of lignocellulosic biomass for multiple advanced bioenergy processes: A review. *Renewable and Sustainable Energy Reviews*, 154: 111871.

Yuko, D. 2005. Potential for electricity generation from bagasse in Kenya. *International Sugar Journal*, 107 (1273): 32-37.

Zabed, H. M., Akter, S., Yun, J., Zhang, G., Zhang, Y. and Qi, X. 2020. Biogas from microalgae: Technologies, challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 117: 109503.

Zadeh, Z. E., Abdulkhani, A., Aboelazayem, O. and Saha, B. 2020. Recent insights into lignocellulosic biomass pyrolysis: A critical review on pretreatment, characterization, and products upgrading. *Processes*, 8 (7): 799.

Zafeer, M., Menezes, R. A., Venkatachalam, H. and Bhat, K. S. 2023. Sugarcane bagasse-based biochar and its potential applications: a review. *Emergent Materials*, 7: 133–161.

Zamri, M., Hasmady, S., Akhiar, A., Ideris, F., Shamsuddin, A., Mofijur, M., Fattah, I. R. and Mahlia, T. 2021. A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste. *Renewable and Sustainable Energy Reviews*, 137: 110637.

Zepeda, L. C., Al-Waili, I., Griffin, G., Shah, K., Bhargava, S. and Parthasarathy, R. 2024. Techno-economic assessment (TEA) and sensitivity analysis for a biochar-based slurry fuel plant. *Energy Conversion and Management*, 306: 118297.

Zhang, J. and Zhang, X. 2019. *The thermochemical conversion of biomass into biofuels*. Woodhead Publishing.

Zhang, L., Yao, Z., Zhao, L., Li, Z., Yi, W., Kang, K. and Jia, J. 2021. Synthesis and characterization of different activated biochar catalysts for removal of biomass pyrolysis tar. *Energy*, 232: 120927.

Zhang, Q., Chang, J., Wang, T. and Xu, Y. 2007. Review of biomass pyrolysis oil properties and upgrading research. *Energy Conversion and Management*, 48 (1): 87-92.

Zheng, X., Xian, X., Hu, L., Tao, S., Zhang, X., Liu, Y. and Lin, X. 2021. Efficient short-time hydrothermal depolymerization of sugarcane bagasse in one-pot for cellulosic ethanol production without solid-liquid separation, water washing, and detoxification. *Bioresource Technology*, 339: 125575.

Zhu, X., Luo, Z., Zhang, Q., He, M. and Tsang, D. C. 2023. Valorization of slow pyrolysis vapor from biomass waste: Comparative study on pyrolysis characteristics, evolved gas evaluation, and adsorption effects. *Bioresource Technology*, 386: 129543.

ZohoBooks. 2019. *Gross Profit vs Net Profit – How are they different*. Available: https://www.zoho.com/books/guides/what-is-the-difference-between-gross-and-net-profit.html#:~:text=What%20is%20gross%20profit%3F,COGS)%20from%20your%20total%20sales. (Accessed July/16/2024).

Zou, R., Wang, C., Qian, M., Huo, E., Kong, X., Wang, Y., Dai, L., Wang, L., Zhang, X. and Mateo, W. C. 2022. Catalytic co-pyrolysis of solid wastes (low-density polyethylene and lignocellulosic biomass) over microwave assisted biochar for bio-oil upgrading and hydrogen production. *Journal of Cleaner Production*, 374: 133971.

Zurita García, L. 2021. Life cycle assessment of bioethanol production from sugarcane bagasse: A case study for Mexico. Master of Science, Monterrey Institute of Technology and Higher Education.

Appendices

Appendix A: Fast Pyrolysis Simulation Aspen Plus Data

Table A 1: Aspen Plus databank conventional components and user-defined nonconventional components applied in the fast pyrolysis Aspen Plus simulation (Gorensek, Shukre, and Chen 2019)

Component ID	Type	Component name	Alias
HEMICELL	solid	Hemicellulose	$C_5H_8O_4$
CELLULOS	solid	Cellulose	C6H10O5
LIG-C	solid	C-rich lignin	C15H14O4
LIG-O	solid	O-rich lignin	C20H22O10
LIG-H	solid	H-rich lignin	C22H28O9
LIG-CC	solid	C-rich lignin intermediate	C5H8O4
LIG-OH	solid	H/O-rich lignin intermediate	C6H10O5
LIG-HMW	solid	High-molecular weight lignin	C24H28O4
LIG	solid	Secondary lignin intermediate	C11H12O4
CHAR	solid	Char	C
HCE-1	solid	Activated hemicellulose 1	C5H8O4
HCE-2	solid	Activated hemicellulose 2	C5H8O4
H2O	Conventional	Water	H2O
FE2MACR	Conventional	Sinapyl aldehyde	C11H12O4
GLYOXAL	Conventional	Glyoxal	C2H2O2
C2H4	Conventional	Ethylene	C2H4
CH3CHO	Conventional	Acetaldehyde	C2H4O-1
ACAC	Conventional	Acetic-acid	C2H4O2-1
HAA	Conventional	Glycol aldehyde	C2H4O2-1
C2H5OH	Conventional	Ethanol	C2H6O-2
ACROL	Conventional	Acrolein	C3H4O
ALD3	Conventional	n-propylene-oxide	C3H6O
C3H6O2-N	Conventional	3-hydroxypropanal	C3H6O2
FURF	Conventional	Furfural	C5H4O2
XYLAN	Conventional	xylosan	C5H8O4
LVG	Conventional	Levoglucosan	C6H10O5
PHENOL	Conventional	Phenol	C6H6O
HMFU	Conventional	5-hydroxymethyl-furfural	C6H6O3
ANISOLE	Conventional	Anisole	C7H8O
COUMARYL	Conventional	p-coumaryl alcohol	C9H10O2
CH2O	Conventional	Formaldehyde	CH2O
CO	Conventional	Carbon-monoxide	CO
CO2	Conventional	Carbon-dioxide	CO2
H2	Conventional	Hydrogen	H2
ASH	Nonconventional	Ash	
SCB	Nonconventional	Sugarcane bagasse	
HCOOH	Conventional	Formic-acid	CH2O2
CH4	Conventional	Methane	CH4
CH3OH	Conventional	Methanol	CH4O

Table A 1: Properties used to define components that are not available in Aspen plus data base (Gorensek, Shukre and Chen 2019)

Component ID	Component name	Molecular Weight (kg/kmol)	Enthalpy of formation (kJ/kmol)	Heat capacity coefficients		Solid density ($kmol/m^3$)
				C_1(J/kmol.K)	C_2(J/kmol.K)	
LIG-C	C-rich lignin	258.27376	-759390	16404,8	1027,49	5.8852
LIG-O	O-rich lignin	422.38868	-1847500	26828,9	1680,39	3.5986
LIG-H	H-rich lignin	436.45892	-1722700	27722,6	1736,36	3.4826
LIG-CC	C-rich lignin intermediate	258.27376	-759390	16404,8	1027,49	5.8852
LIG-OH	H/O-rich lignin intermediate	378.37888	-1429200	24033,5	1505,3	4.0171
LIG-HMW	High-molecular weight lignin	380.48392	-958260	24167,2	1513,68	3.9949

Appendix B: Simulation Reports

Mass balance Results from Aspen Plus simulations

Table B 1: Pre-treatment Aspen Plus simulation report

Stream Name	Units	SCB	AIR	SULPHUR	LPS	SCB-2	LPS-1	HYD-1	HYD-2	V-1	HYD-3
From						M-2		R-2	F-1	F-1	C-1
To		M-1	R-1	H-1	M-1	R-2	R-2	F-1	C-1		
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	25	25	25	130	83.44458748	130	190	100	100	30
Pressure	bar	1	1	1	2.70	1	2.70	1	1	1	1
Mass Vapor Fraction		0.00	1.00	0.00	1.00	0.04	0.00	0.19	0.00	1.00	0.00
Mass Liquid Fraction		0.12	0.00	0.00	0.00	0.16	1.00	0.57	0.74	0.00	0.74
Mass Solid Fraction		0.88	0.00	1.00	0.00	0.81	0.00	0.25	0.26	0.00	0.26
Mass Enthalpy	cal/gm	-1789.56	-0.06	0.00	-3160.69	-1824.97	-3684.21	-1675.30	-1794.85	-1898.54	-1840.21
Mass Density	gm/cc	1.25	0.00	2.05	0.00	0.02	0.93	0.00	1.19	0.00	1.24
Enthalpy Flow	cal/sec	-25769683.58	-19.03	0.00	-2638242.57	-28559450.28	-4305322.49	-28175040.08	-28626667.56	-1648861.50	-29350134.61
Mass Flows	**kg/hr**	**51840.00**	**1232.99**	**259.47**	**3004.94**	**56337.40**	**4206.92**	**60544.32**	**57417.76**	**3126.56**	**57417.76**
CELLULOS	kg/hr	24279.97	0.00	0.00	0.00	24279.97	0.00	6198.68	6198.68	0.00	6198.68
HEMICELL	kg/hr	12661.56	0.00	0.00	0.00	12661.56	0.00	405.17	405.17	0.00	405.17
LIGNIN	kg/hr	5644.08	0.00	0.00	0.00	5644.08	0.00	5644.08	5644.08	0.00	5644.08
ASH	kg/hr	2779.92	0.00	0.00	0.00	2779.92	0.00	2779.92	2779.92	0.00	2779.92
SO2	kg/hr	0.00	0.00	0.00	0.00	518.40	0.00	518.40	92.16	426.24	92.16
WATER	kg/hr	6474.46	0.00	0.00	3004.94	9479.40	4206.92	10006.08	8276.82	1729.26	8276.82
GLUCOSE	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	20090.27	20090.27	0.00	20090.27
XYLOSE	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	13927.67	13927.67	0.00	13927.67
ETHANOL	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SULFUR	kg/hr	0.00	0.00	259.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN	kg/hr	0.00	974.06	0.00	0.00	974.06	0.00	974.06	3.00	971.06	3.00
OXYGEN	kg/hr	0.00	258.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B 2: Enzyme Production simulation report

Stream Name	Units	AIR	AMMONIA	DAP	HYDROLY	MICROORG	ENZYME
From							R-3
To		R-3	M-3	M-3	M-3	M-3	
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	25.00	25.00	25.00	25.00	25.00	30.00
Pressure	bar	1.01	1.01	1.01	1.01	1.01	1.01
Mass Vapor Fraction		1.00	1.00	0.00	0.00	1.00	0.36
Mass Liquid Fraction		0.00	0.00	1.00	0.73	0.00	0.45
Mass Solid Fraction		0.00	0.00	0.00	0.27	0.00	0.19
Mass Enthalpy	cal/gm	-0.06	-644.39	-2150.57	-1846.07	0.12	-1376.29
Mass Density	gm/cc	0.00	0.00	1.00	1.47	0.00	0.00
Enthalpy Flow	cal/sec	-27.35	-77038.25	-17138.82	-2942754.88	1.51	-3054654.26
Mass Flows	**kg/hr**	**1746.54**	**430.39**	**28.69**	**5738.64**	**45.91**	**7990.17**
CELLULOS	kg/hr	0.00	0.00	0.00	636.51	0.00	636.51
HEMICELL	kg/hr	0.00	0.00	0.00	48.96	0.00	48.96
LIGNIN	kg/hr	0.00	0.00	0.00	564.41	0.00	564.41
ASH	kg/hr	0.00	0.00	0.00	277.99	0.00	277.99
SO2	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
WATER	kg/hr	0.00	0.00	0.00	832.36	0.00	832.36
GLUCOSE	kg/hr	0.00	0.00	0.00	2007.46	0.00	903.36
XYLOSE	kg/hr	0.00	0.00	0.00	1370.95	0.00	1370.95
ETHANOL	kg/hr	0.00	0.00	0.00	0.00	0.00	564.67
CO2	kg/hr	0.00	0.00	0.00	0.00	0.00	539.43
SULFUR	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN	kg/hr	1344.84	0.00	0.00	0.00	0.00	1344.84
OXYGEN	kg/hr	401.70	0.00	0.00	0.00	0.00	401.70
AMMONIA	kg/hr	0.00	430.39	0.00	0.00	0.00	430.39
DIAMM-01	kg/hr	0.00	0.00	28.69	0.00	0.00	28.69
MICROORG	kg/hr	0.00	0.00	0.00	0.00	45.91	45.91

Table B 3: Bioethanol fermentation simulation report

Stream Name	Units	HYDROLY	ENZYME	S1	AMMONIA	S2	V-1	CO2FLASH	BROTH	WATER	CO2FL-1	BROTH-R	F-BROTH
From				M-4		R-4		B1	B1		B4	B4	B5
To		M-4	M-4	R-4	R-4	B1	B1	B4	B5	B4		B5	
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	30.00	30.00	30.00	25.00	30.00	100.00	30.00	30.00	25.00	40.98	40.98	39.46
Pressure	bar	1.01	1.01	1.01	1.01	1.01	1.00	1.01	1.01	1.01	1.00	1.00	1.00
Mass Vapor Fraction		0.34	0.36	0.34	1.00	0.49	1.00	1.00	0.00	0.00	1.00	0.00	0.00
Mass Liquid Fraction		0.43	0.45	0.43	0.00	0.35	0.00	0.00	0.70	1.00	0.00	1.00	0.90
Mass Solid Fraction		0.23	0.19	0.22	0.00	0.17	0.00	0.00	0.30	0.00	0.00	0.00	0.10
Mass Enthalpy	cal/gm	-1331.30	-1365.66	-1335.91	-644.39	-1336.17	-1898.54	-963.57	-1771.18	-3789.48	-1030.19	-3621.50	-2994.12
Enthalpy Flow	cal/sec	-19099686.69	-3031069.26	-22130757.37	-46224.02	-22230936.30	-1648861.50	-8112341.16	-16095185.41	-63808528.38	-7771713.30	-64149156.23	-80244341.64
Mass Flows	**kg/hr**	**51647.75**	**7990.17**	**59637.93**	**258.24**	**59896.17**	**3126.56**	**30308.51**	**32714.21**	**60618.00**	**27158.28**	**63768.24**	**96482.45**
CELLULOS	kg/hr	3924.10	636.51	4560.61	0.00	1164.32	0.00	0.00	1164.32	0.00	0.00	0.00	1164.32
HEMICELL	kg/hr	301.85	48.96	350.82	0.00	350.82	0.00	0.00	350.82	0.00	0.00	0.00	350.82
LIGNIN	kg/hr	5079.67	564.41	5644.08	0.00	5644.08	0.00	0.00	5644.08	0.00	0.00	0.00	5644.08
ASH	kg/hr	2501.93	277.99	2779.92	0.00	2779.92	0.00	0.00	2779.92	0.00	0.00	0.00	2779.92
SO2	kg/hr	0.00	0.00	0.00	0.00	0.00	426.24	412.14	14.10	0.00	390.78	21.36	35.46
WATER	kg/hr	5131.52	832.36	5963.88	0.00	5586.53	1729.26	545.48	6770.31	60618.00	1355.58	59807.90	66578.21
GLUCOSE	kg/hr	5569.21	903.36	6472.56	0.00	4388.54	0.00	0.00	4388.54	0.00	0.00	0.00	4388.54
XYLOSE	kg/hr	8451.92	1370.95	9822.86	0.00	2302.48	0.00	0.00	2302.48	0.00	0.00	0.00	2302.48
ETHANOL	kg/hr	3481.21	564.67	4045.88	0.00	10887.82	0.00	2647.00	8240.82	0.00	519.01	2127.99	10368.81
CO2	kg/hr	3325.60	539.43	3865.03	0.00	10401.15	0.00	10390.96	10.19	0.00	10375.71	15.25	25.44
SULFUR	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN	kg/hr	8290.95	1344.84	9635.79	0.00	9635.79	971.06	10592.85	13.99	0.00	10536.36	56.49	70.49
OXYGEN	kg/hr	2476.52	401.70	2878.22	0.00	2878.22	0.00	2868.41	9.81	0.00	2829.84	38.58	48.39
AMMONIA	kg/hr	2653.36	430.39	3083.75	258.24	3341.99	0.00	2522.73	819.26	0.00	822.07	1700.67	2519.93
DIAMM-01	kg/hr	176.87	28.69	205.56	0.00	205.56	0.00	0.00	205.56	0.00	0.00	0.00	205.56
MICROORG	kg/hr	283.04	45.91	328.95	0.00	328.95	0.00	328.95	0.00	0.00	328.95	0.00	0.00

Table B 4: Bioethanol purification simulation report

Stream Name	Units	BROTH	BOTTOMS	DISTILLA	DIST-1	BOTT-1	ETHANOL	RESIDUE
From			B5	B5	B1	B1	B2	B2
To		B5		B1	B2			
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	25.00	109.02	65.02	60.78	99.34	60.78	60.78
Pressure	bar	1.00	1.32	1.01	1.01	1.01	1.01	1.01
Mass Vapor Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass Liquid Fraction		0.90	0.68	1.00	1.00	1.00	1.00	1.00
Mass Solid Fraction		0.10	0.32	0.00	0.00	0.00	0.00	0.00
Mass Enthalpy	cal/gm	-3040.68	-2281.03	-3291.27	-3228.00	-3705.25	-1425.50	-3605.16
Mass Density	gm/cc	1.02	1.19	0.91	0.91	0.96	0.76	0.69
Enthalpy Flow	cal/sec	-81492183.88	-16737000.29	-62921988.31	-53574376.68	-9341142.01	-4099666.44	-49465784.81
Mass Flows	**kg/hr**	**96482.40**	**26143.03**	**68824.23**	**59748.44**	**9075.79**	**10353.44**	**49394.99**
CELLULOS	kg/hr	1164.32	0.00	0.00	0.00	0.00	0.00	0.00
HEMICELL	kg/hr	350.82	0.00	0.00	0.00	0.00	0.00	0.00
LIGNIN	kg/hr	5644.08	5644.08	0.00	0.00	0.00	0.00	0.00
ASH	kg/hr	2779.92	2779.92	0.00	0.00	0.00	0.00	0.00
SO2	kg/hr	35.46	0.02	35.44	35.41	0.03	0.00	35.41
WATER	kg/hr	66578.17	10785.66	55792.51	46754.12	9038.39	46.75	46707.37
GLUCOSE	kg/hr	4388.54	4388.54	0.00	0.00	0.00	0.00	0.00
XYLOSE	kg/hr	2302.48	2302.48	0.00	0.00	0.00	0.00	0.00
ETHANOL	kg/hr	10368.81	31.11	10337.70	10306.69	31.01	10306.69	0.00
CO2	kg/hr	25.44	0.00	25.44	25.44	0.00	0.00	25.44
SULFUR	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN	kg/hr	70.49	0.00	70.49	70.49	0.00	0.00	70.49
OXYGEN	kg/hr	48.39	0.00	48.39	48.39	0.00	0.00	48.39
AMMONIA	kg/hr	2519.92	5.65	2514.27	2507.91	6.37	0.00	2507.91
DIAMM-01	kg/hr	205.56	205.56	0.00	0.00	0.00	0.00	0.00
MICROORG	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B 5: Anaerobic digestion simulation report

Stream Name	Units	HYDR	DIGESTAT	WATER	BIOGAS	CO2
From			S-L-SEP	FLASH	SEP	SEP
To		ACIDO				
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	37	37	53	53	53
Pressure	bar	3	3	1	1	1
Mass Vapor Fraction		0.00	0.00	0.00	1.00	0.92
Mass Liquid Fraction		0.85	1.00	0.71	0.00	0.08
Mass Solid Fraction		0.15	0.00	0.29	0.00	0.00
Mass Enthalpy	cal/gm	-1816.32	-1614.98	-1940.17	-1094.35	-2188.14
Mass Density	gm/cc	1.32	1.10	1.09	0.00	0.00
Enthalpy Flow	cal/sec	-28969115.44	-2962525.80	-15811089.39	-1537131.06	-9980153.75
Mass Flows	**kg/hr**	**57417.76**	**6603.85**	**29337.64**	**5056.57**	**16419.71**
CELLULOS	kg/hr	6198.68	6198.68	0.00	0.00	0.00
HEMICELL	kg/hr	405.17	405.17	0.00	0.00	0.00
LIGNIN	kg/hr	5644.08	0.00	5644.08	0.00	0.00
ASH	kg/hr	2779.92	0.00	2779.92	0.00	0.00
SO2	kg/hr	92.16	0.00	7.79	0.00	84.37
WATER	kg/hr	8276.82	0.00	7108.44	0.00	1167.26
GLUCOSE	kg/hr	20090.27	0.00	0.00	0.00	0.00
XYLOSE	kg/hr	13927.67	0.00	0.00	0.00	0.00
CO2	kg/hr	0.00	0.00	103.02	0.00	13795.26
NITROGEN	kg/hr	3.00	0.00	0.00	0.00	1.84
CH4	kg/hr	0.00	0.00	8.73	5056.57	0.00
H2S	kg/hr	0.00	0.00	0.00	0.00	0.00
NH3	kg/hr	0.00	0.00	0.19	0.00	1.22
METHY-01	kg/hr	0.00	0.00	0.00	0.00	0.00
ACETI-01	kg/hr	0.00	0.00	13685.46	0.00	1369.76
HYDROGEN	kg/hr	0.00	0.00	0.00	0.00	0.00

Table B 6: Dark fermentation Aspen Plus simulation report

Stream Name	Units	HYDR	DIGESTAT	ACETIC	WATER	HYDROGEN	CO2
From			S-L-SEP	L-L-SEP	FLASH	SEP	SEP
To		ACIDO					
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	37	37	37	53	53	53
Pressure	bar	3	3	3	1	1	1
Mass Vapor Fraction		0.00	0.00	0.00	0.00	1.00	0.84
Mass Liquid Fraction		0.85	0.44	1.00	1.00	0.00	0.16
Mass Solid Fraction		0.15	0.56	0.00	0.00	0.00	0.00
Mass Enthalpy	cal/gm	-1816	-1058	-1814	-2164	96	-2153
Mass Density	gm/cc	1	1	1	1	0	0
Enthalpy Flow	cal/sec	-28969115	-4414707	-7542499	-4697288	33861	-10968552
Mass Flows	**kg/hr**	**57418**	**15028**	**14967**	**7813**	**1273**	**18337**
CELLULOS	kg/hr	6199	6199	0	0	0	0
HEMICELL	kg/hr	405	405	0	0	0	0
LIGNIN	kg/hr	5644	5644	0	0	0	0
ASH	kg/hr	2780	2780	0	0	0	0
SO2	kg/hr	92	0	0	2	0	90
WATER	kg/hr	8277	0	0	1419	0	1168
GLUCOSE	kg/hr	20090	0	0	0	0	0
XYLOSE	kg/hr	13928	0	0	0	0	0
ETHANOL	kg/hr	0	0	0	0	0	0
CO2	kg/hr	0	0	0	21	0	13878
SULFUR	kg/hr	0	0	0	0	0	0
NITROGEN	kg/hr	3	0	0	0	0	3
OXYGEN	kg/hr	0	0	0	0	0	0
CH4	kg/hr	0	0	0	0	0	0
H2S	kg/hr	0	0	0	0	0	0
NH3	kg/hr	0	0	0	0	0	0
METHY-01	kg/hr	0	0	0	0	0	0
ACETI-01	kg/hr	0	0	14967	6371	0	3198
HYDROGEN	kg/hr	0	0	0	0	1273	0
CO	kg/hr	0	0	0	0	0	0

Table B 7: Gasification simulation report

Stream Name	Units	BIOMASS	STEAM	GASMIX	GAS	SOLID	SYNGAS	WATER
From				GASIFIER	SOLIDSEP	SOLIDSEP	GASSEP	GASSEP
To		DRYER	COMBUST	SOLIDSEP	COOLER			
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	24.85	110	800	800.0000017	800	45	45
Pressure	bar	1.00	1.01	1.00	1.00	1.00	1.00	1.00
Mass Vapor Fraction		0.00	1.00	0.98	1.00	0.00	1.00	0.00
Mass Liquid Fraction		0.50	0.00	0.00	0.00	0.00	0.00	1.00
Mass Solid Fraction		0.50	0.00	0.02	0.00	1.00	0.00	0.00
Mass Enthalpy	cal/gm	-2566.76	-3168.82	-1495.95	-1519.69	-7.69	-1399.34	-3783.47
Mass Density	gm/cc	1.12	0.00	0.00	0.00	3.49	0.00	0.27
Enthalpy Flow	cal/sec	-36961412.61	-12569666.60	-11319383.19	-11318469.75	-913.43	-7463829.64	-7998376.20
Mass Flows	**kg/hr**	**51840.00**	**14280.00**	**27240.00**	**26812.32**	**427.68**	**19201.81**	**7610.51**
BIOMASS	kg/hr	25920.00	0.00	0.00	0.00	0.00	0.00	0.00
ASH	kg/hr	0.00	0.00	427.68	0.00	427.68	0.00	0.00
O2	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	kg/hr	0.00	0.00	8696.99	8696.99	0.00	8696.99	0.00
CO	kg/hr	0.00	0.00	8983.80	8983.80	0.00	8983.80	0.00
N2	kg/hr	0.00	0.00	19.39	19.39	0.00	0.00	19.39
H2O	kg/hr	25920.00	14280.00	7591.06	7591.06	0.00	0.00	7591.06
S	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H2S	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NH3	kg/hr	0.00	0.00	0.06	0.06	0.00	0.00	0.06
H2	kg/hr	0.00	0.00	1510.45	1510.45	0.00	1510.45	0.00
CH4	kg/hr	0.00	0.00	10.57	10.57	0.00	10.57	0.00

Table B 8: Pyrolysis Aspen Plus simulation report

Stream Name	Units	WETSCB	DRYSCB	SOLID	GAS	WATER	BIO-OIL
From			SEP	CYCLONE	B5	B1	B1
To		HEATER-1	HEATER-2				
Stream Class		MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC	MIXCINC
Temperature	C	25	100	500	30	30	30
Pressure	bar	1.01	1.01	1.01	2.03	2.03	2.03
Mass Vapor Fraction		0.00	0.00	0.00	1.00	0.00	0.12
Mass Liquid Fraction		0.50	0.00	0.00	0.00	1.00	0.66
Mass Solid Fraction		0.50	1.00	1.00	0.00	0.00	0.22
Mass Enthalpy	cal/gm	-2400.01	-959.12	-272.12	-1437.75	-3807.10	-1068.95
Mass Density	gm/cc	1.02	1.27	1.80	0.00	0.85	0.02
Enthalpy Flow	cal/sec	-34560118.65	-6905650.50	-471673.23	-1568106.27	-2918789.99	-3858161.95
Mass Flows	kg/hr	51840.00	25920.00	6240.09	3926.39	2760.01	12993.51
LIG-C	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
LIG-O	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
LIG-H	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
HEMICELL	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
CELLULOS	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
LIG	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
LIG-CC	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
LIG-OH	kg/hr	0.00	0.00	3292.98	0.00	0.00	0.00
HCE-1	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
HCE-2	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
LIG-HMW	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
CHAR	kg/hr	0.00	0.00	2947.11	0.00	0.00	0.00
H2O	kg/hr	25920.00	0.00	0.00	0.00	2760.01	0.00
FE2MACR	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
GLYOXAL	kg/hr	0.00	0.00	0.00	0.00	0.00	126.74
C2H4	kg/hr	0.00	0.00	0.00	0.00	0.00	494.01
CH3CHO	kg/hr	0.00	0.00	0.00	0.00	0.00	144.72
ACAC	kg/hr	0.00	0.00	0.00	0.00	0.00	708.32
HAA	kg/hr	0.00	0.00	0.00	0.00	0.00	731.88
C2H5OH	kg/hr	0.00	0.00	0.00	0.00	0.00	155.25
ACROL	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
ALD3	kg/hr	0.00	0.00	0.00	0.00	0.00	569.49
C3H6O2-N	kg/hr	0.00	0.00	0.00	0.00	0.00	215.55
FURF	kg/hr	0.00	0.00	0.00	0.00	0.00	174.36
XYLAN	kg/hr	0.00	0.00	0.00	0.00	0.00	719.22
LVG	kg/hr	0.00	0.00	0.00	0.00	0.00	3551.04
PHENOL	kg/hr	0.00	0.00	0.00	0.00	0.00	102.11
HMFU	kg/hr	0.00	0.00	0.00	0.00	0.00	690.49
ANISOLE	kg/hr	0.00	0.00	0.00	0.00	0.00	0.00
COUMARYL	kg/hr	0.00	0.00	0.00	0.00	0.00	222.68
CH2O	kg/hr	0.00	0.00	0.00	0.00	0.00	748.92
CO	kg/hr	0.00	0.00	0.00	2111.73	0.00	0.00
CO2	kg/hr	0.00	0.00	0.00	1713.87	0.00	0.00
H2	kg/hr	0.00	0.00	0.00	100.79	0.00	0.00
ASH	kg/hr	0.00	0.00	0.00	0.00	0.00	2802.16
SCB	kg/hr	25920.00	25920.00	0.00	0.00	0.00	0.00
HCOOH	kg/hr	0.00	0.00	0.00	0.00	0.00	79.82
CH4	kg/hr	0.00	0.00	0.00	0.00	0.00	327.54
CH3OH	kg/hr	0.00	0.00	0.00	0.00	0.00	429.21

Energy requirements results

Table B 9: Bioethanol production energy requirements results

Heating Duty				Cooling Duty			
Electricity energy requirements				**Electricity energy requirements**			
Parameter	**Value (cal/s)**	**Value (MW)**	**Comment**	**Parameter**	**Value (cal/s)**	**Value (MW)**	**Comment**
Pre-treatment	1117	0.0047	Calculated from heat duties in Aspen	Pre-treatment	723464.00	3.03	Calculated from heat duties in Aspe
Enzyme Production		0	ASPEN	Enzyme Production		0.00	ASPEN
Fermentation		0	ASPEN	Fermentation		0.00	ASPEN
Purification	21930684.00	91.82		Purification	21930684.00	91.82	
Total	**91.82**	**MW**		**Total**	**94.85**	**MW**	
Steam energy requirements	Pre-treatment						
Parameter	**Value**	**Units**	**Comment**				
Steam mass	7212	kg/hr					
Steam Pressure	3	Bar					
Steam Pressure	0.3	MPa					
Steam sensible heat	561.45	KJ/kg	(h_1) Steam table @steam pressure				
Steam Latent heat of evaporatio	2725.3	KJ/kg	(Δhv)Steam table @steam pressure				
Feed water Temperature	20	°C					
Water sensible heat	83.94	KJ/kg	(h_1) Steam table @feed water temperature				
Energy required to produce stea	3202.81	KJ/kg					
Energy required to produce stea	23098665.72	KJ/h					
Energy required to produce stea	6416.30	KW					
Energy required to produce stea	6.42	MW					
Total heating Duty	**98.24**	**MW**					

Table B 10: Biogas production energy requirements results

Heating Duty			
Electricity energy requirements			
Parameter	**Value (cal/s)**	**Value (MW)**	**Comment**
Pretreatment	4917000	20.59	Calculated from heat duties in Aspen
Anaerobic digestion and purification	1941000	8.13	Aspen Energy analyser
Total	**28.713**	**MW**	
Cooling Duty			
Electricity energy requirements			
Parameter	**Value (cal/s)**	**Value (MW)**	**Comment**
Pre-treatment	3085000.00	12.92	Calculated from heat duties in Aspen
Anaerobic digestion and Purification	3158000.00	13.22	Aspen Energy analyser
Total	**26.14**	**MW**	

Table B 11: Biohydrogen production energy requirements results

Heating Duty			
Electricity energy requirements			
Parameter	**Value (cal/s)**	**Value (MW)**	**Comment**
Pretreatment	4917000	20.59	Calculated from heat duties in Aspen
Biohydrogen	1.99E+06	8.34	Aspen Energy analyser
Total	**28.93**	**MW**	
Cooling Duty			
Electricity energy requirements			
Parameter	**Value (cal/s)**	**Value (MW)**	**Comment**
Pre-treatment	3085000.00	12.92	Calculated from heat duties in Aspen
Biohydrogen	420200.00	1.76	Aspen Energy analyser
Total	**14.68**	**MW**	

Table B 12: Gasification production energy requirements results

Heating Duty				Cooling Duty			
Electricity energy requirements				**Electricity energy requirements**			
Parameter	**Value (cal/s)**	**Value (MW)**	**Comment**	**Parameter**	**Value (cal/s)**	**Value (MW)**	**Comment**
Drying (heating to 110 ℃)	1877216	7.859527949	Calculated from heat duties in Aspen	Cooling to 45 ℃	3803726	15.93	Calculated from heat duties in Aspen
Heating to 800℃	5864983	24.55551082					
Total	**32.41503877**	**MW**		**Total**	**15.93**	**MW**	
Steam energy requirements	Pre-treatment						
Parameter	**Value**	**Units**	**Comment**				
Steam mass	14280	kg/hr					
Steam Pressure	3	Bar					
Steam Pressure	0.3	MPa					
Steam sensible heat	561.45	KJ/kg	(h_1) Steam table @steam pressure				
Steam Latent heat of evaporation	2725.3	KJ/kg	(Δhv)Steam table @steam pressure				
Feed water Temperature	20	℃					
Water sensible heat	83.94	KJ/kg	(h_1) Steam table @feed water temperature				
Energy required to produce steam	3202.81	KJ/kg					
Energy required to produce steam	45736126.8	KJ/h					
Energy required to produce steam	12704.48	KW					
Energy required to produce steam	12.70	MW					
Total heating Duty	**45.12**	**MW**					

Table B 13: Pyrolysis production energy requirements results

Heating Duty				Cooling Duty			
Electricity energy requirements				Electricity energy requirements			
Parameter	Value (cal/s	Value (MW)	Comment	Parameter	Value (cal/s)	Value (MW)	Comment
Drying (heating to 100 °C)	788676	3.30	Calculated from heat duties in Aspen	Cooling to 30 °	1861283	7.79	Calculated from heat duties in Aspen
Heating to 500°C	1544422	6.47					
Total	9.768	MW		Total	7.79	MW	

Appendix C: Equipment Costs Results from Aspen Plus Simulations

Table C 1: Pre-treatment costing for biological processes

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	F-1	31 000	208 900	5800	28999
▶	H-1	0	0	0	0
▶	R-1	0	0	0	0
▶	M-2	0	0	0	0
▶	R-2	103 800	263 600	11400	29683
▶	C-1	72 400	197 400	18800	44486
▶	M-1	0	0	0	0

Table C 2: Enzyme production Costing for bioethanol Production

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	M-3	0	0	0	0
▶	R-3	62 300	210 900	5000	20044

Table C 3: Bioethanol fermentation equipment costing

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	B5	0	0	0	0
▶	B1	25 700	157 800	4600	22796
▶	M-4	0	0	0	0
▶	R-4	102 500	257 100	10700	27242
▶	B4	0	0	0	0

Table C 4: Bioethanol purification equipment costing

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	MS	20 100	130 300	3400	14270
▶	C-1	96 200	296 500	18900	45708
▶	C-2	133 200	346 000	26000	54678

Table C 5: **Anaerobic digestion costing**

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	ACETO	118 900	275 800	13700	30838
▶	FLASH	23 900	135 400	3900	15099
▶	B3	24 200	136 300	4100	15359
▶	B4	9 200	71 200	540	8474
▶	SEP	31 700	180 000	6300	21753
▶	ACIDO	118 900	275 800	13700	30838
▶	METHANO	103 600	258 600	11300	27946

Table C 6: Dark fermentation costing

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	ACETO	118 900	275 800	13700	30838
▶	FLASH	23 900	135 400	3900	15099
▶	B3	24 200	136 300	4100	15359
▶	B4	9 200	71 200	540	8474
▶	SEP	31 700	180 000	6300	21753
▶	ACIDO	118 900	275 800	13700	30838

Table C 7: Gasification equipment costing

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	COMBUST	0	0	0	0
▶	SOLIDSEP	0	0	0	0
▶	GASIFIER	0	0	0	0
▶	DRYER	103 200	257 900	11100	27682
▶	SEP	46 700	228 800	12700	40149
▶	COOLER	0	0	0	0
▶	GASSEP	38 100	215 100	9500	34885
▶	DECOMP	0	0	0	0

Table C 8: Pyrolysis equipment costing

	Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
▶	B1	16 400	103 600	2600	10317
▶	HEATER-2	0	0	0	0
▶	HEATER-1	14 700	91 600	2300	15024
▶	RSTOICH2	0	0	0	0
▶	DECOMP	0	0	0	0
▶	B5	20 100	130 300	3400	14270
▶	RSTOICH1	0	0	0	0
▶	SEP	24 300	146 100	4100	19213
▶	COOLER	39 500	181 900	3900	16852
▶	CYCLONE	47 600	313 200	3800	28431

Appendix D: Cashflow Analyses Results

Table D 1: Bioethanol production cashflow analyses

Year	Project year	Investment ($)	Gross Profit ($)	Depreciation expense ($)	Taxable income ($)	Tax paid ($)	Net Cash flow ($)	Discount factor	Discount cash flow ($
2023	0	0	0	0	0	0	0	0	0
2024	0	9351325.87	0.00	0.00	0.00	0.00	-9351325.87	1.00	-9351325.87
2025	1	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.89	-4974445.14
2026	2	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.80	-4441468.88
2027	3	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.71	-3965597.21
2028	4	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.64	-3540711.79
2029	5	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.57	-3161349.82
2030	6	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.51	-2822633.77
2031	7	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.45	-2520208.72
2032	8	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.40	-2250186.36
2033	9	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.36	-2009094.96
2034	10	0.00	-7179611.54	-1435922.31	-5743689.23	-1608232.99	-5571378.56	0.32	-1793834.79
2035	11	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.29	-1486056.06
2036	12	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.26	-1326835.77
2037	13	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.23	-1184674.80
2038	14	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.20	-1057745.35
2039	15	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.18	-944415.49
2040	16	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.16	-843228.12
2041	17	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.15	-752882.25
2042	18	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.13	-672216.29
2043	19	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.12	-600193.12
2044	20	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.10	-535886.71
2045	21	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.09	-478470.28
2046	22	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.08	-427205.61
2047	23	0.00	-7179611.54	0.00	-7179611.54	-2010291.23	-5169320.31	0.07	-381433.58
2048	24	1.00	-7179611.54	1.00	-7179612.54	-2010291.51	-5169320.03	0.07	-340565.68

Table D 2: Biogas production cashflow analyses

Year	Project year	Investment ($)	Gross Profit ($)	Depreciation e	Taxable income ($)	Tax paid ($)	Net Cash flow ($)	Discount factor	Discount cash flow ($)
2023	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2024	0	6420973.44	0.00	0.00	0.00	0.00	-6420973.44	1.00	-6420973.44
2025	1	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.89	5147497.50
2026	2	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.80	4595979.91
2027	3	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.71	4103553.49
2028	4	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.64	3663887.05
2029	5	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.57	3271327.72
2030	6	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.51	2920828.32
2031	7	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.45	2607882.43
2032	8	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.40	2328466.46
2033	9	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.36	2078987.91
2034	10	0.00	7429377.84	1485875.57	5943502.27	1664180.64	5765197.20	0.32	1856239.20
2035	11	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.29	1537753.39
2036	12	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.26	1372994.10
2037	13	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.23	1225887.59
2038	14	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.20	1094542.49
2039	15	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.18	977270.08
2040	16	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.16	872562.57
2041	17	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.15	779073.72
2042	18	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.13	695601.54
2043	19	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.12	621072.80
2044	20	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.10	554529.29
2045	21	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.09	495115.44
2046	22	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.08	442067.35
2047	23	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.07	394702.99
2048	24	0.00	7429377.84	0.00	7429377.84	2080225.80	5349152.04	0.07	352413.39

Table D 3: Biohydrogen production cashflow analyses

Year	Project year	Investment ($)	Gross Profit ($)	Depreciation expense ($)	Taxable income ($)	Tax paid ($)	Net Cash flow ($)	Discount factor	Discount cash flow ($)
2023	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2024	0	8483327.53	0.00	0.00	0.00	0.00	-8483327.53	1.00	-8483327.53
2025	1	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.89	8880161.81
2026	2	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.80	7928715.90
2027	3	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.71	7079210.62
2028	4	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.64	6320723.77
2029	5	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.57	5643503.37
2030	6	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.51	5038842.29
2031	7	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.45	4498966.33
2032	8	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.40	4016934.23
2033	9	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.36	3586548.42
2034	10	0	12816728.38	2563345.68	10253382.71	2870947.16	9945781.22	0.32	3202275.37
2035	11	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.29	2652842.26
2036	12	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.26	2368609.16
2037	13	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.23	2114829.61
2038	14	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.20	1888240.72
2039	15	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.18	1685929.22
2040	16	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.16	1505293.94
2041	17	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.15	1344012.45
2042	18	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.13	1200011.12
2043	19	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.12	1071438.50
2044	20	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.10	956641.51
2045	21	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.09	854144.21
2046	22	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.08	762628.76
2047	23	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.07	680918.53
2048	24	0	12816728.38	0.00	12816728.38	3588683.95	9228044.44	0.07	607962.98

Table D 4: Gasification cashflow analyses

Year	Project year	Investment ($)	Gross Profit ($)	Depreciation expense ($)	Taxable income ($)	Tax paid ($)	Net Cash flow ($)	Discount factor	Discount cash flow ($)
2023	0		0.00	0.00	0.00	0.00	0.00	0.00	0.00
2024	0	3172714.77	0.00	0.00	0.00	0.00	-3172714.77	1.00	-3172714.77
2025	1	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.89	3086958.39
2026	2	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.80	2756212.85
2027	3	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.71	2460904.33
2028	4	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.64	2197236.01
2029	5	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.57	1961817.86
2030	6	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.51	1751623.09
2031	7	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.45	1563949.19
2032	8	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.40	1396383.21
2033	9	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.36	1246770.72
2034	10	0.00	4455403.86	891080.77	3564323.09	998010.47	3457393.40	0.32	1113188.14
2035	11	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.29	922191.94
2036	12	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.26	823385.66
2037	13	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.23	735165.77
2038	14	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.20	656398.01
2039	15	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.18	586069.65
2040	16	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.16	523276.48
2041	17	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.15	467211.14
2042	18	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.13	417152.80
2043	19	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.12	372457.86
2044	20	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.10	332551.66
2045	21	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.09	296921.13
2046	22	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.08	265108.15
2047	23	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.07	236703.70
2048	24	0.00	4455403.86	0.00	4455403.86	1247513.08	3207890.78	0.07	211342.59

Table D 5: Pyrolysis cashflow analyses

Year	Project year	Investment ($)	Gross Profit ($)	Depreciation expense ($)	Taxable income ($)	Tax paid ($)	Net Cash flow ($)	Discount factor	Discount cash flow ($)
2023	0		0.00	0.00	0.00	0.00	0.00	0.00	0.00
2024	0	4370281.23	0.00	0.00	0.00	0.00	-4370281.23	1.00	-4370281.23
2025	1	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.89	23784658.13
2026	2	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.80	21236301.90
2027	3	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.71	18960983.84
2028	4	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.64	16929449.86
2029	5	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.57	15115580.23
2030	6	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.51	13496053.78
2031	7	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.45	12050048.02
2032	8	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.40	10758971.44
2033	9	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.36	9606224.50
2034	10	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.32	8576986.16
2035	11	0.00	34328372.56	6865674.51	27462698.05	7689555.45	26638817.11	0.29	7658023.36
2036	12	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.26	6344091.52
2037	13	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.23	5664367.43
2038	14	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.20	5057470.92
2039	15	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.18	4515599.03
2040	16	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.16	4031784.85
2041	17	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.15	3599807.90
2042	18	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.13	3214114.20
2043	19	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.12	2869744.82
2044	20	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.10	2562272.16
2045	21	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.09	2287743.00
2046	22	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.08	2042627.68
2047	23	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.07	1823774.71
2048	24	0.00	34328372.56	0.00	34328372.56	9611944.32	24716428.24	0.07	1628370.28

Appendix E: Lifecycle Assessment

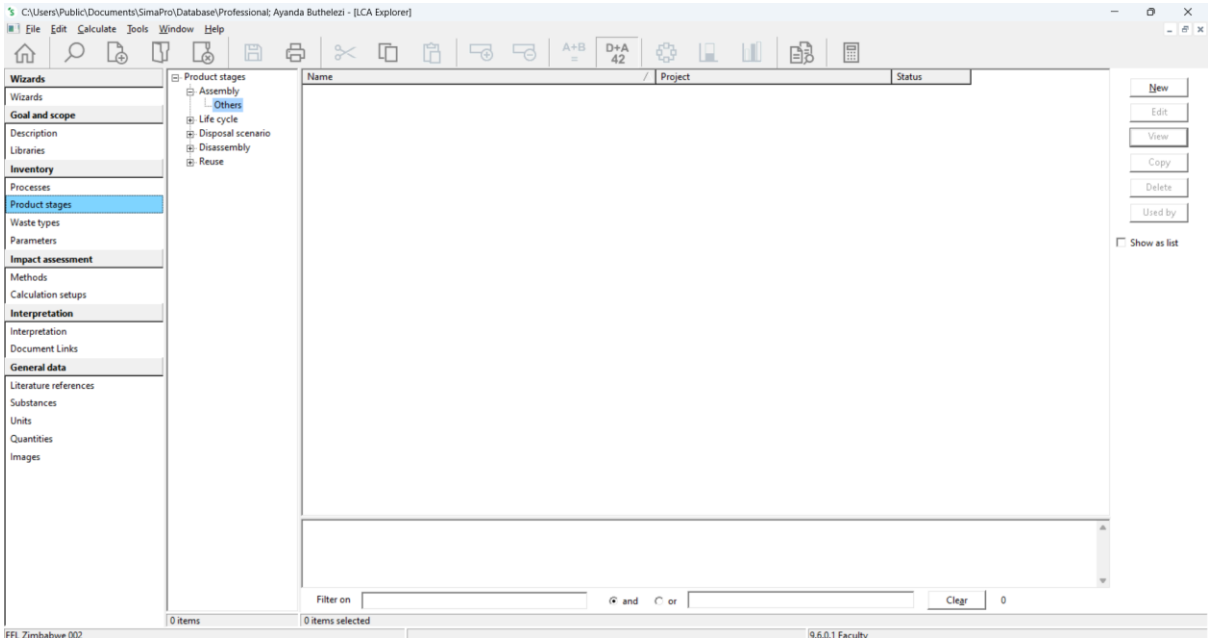

Figure E 1: SimaPro interface

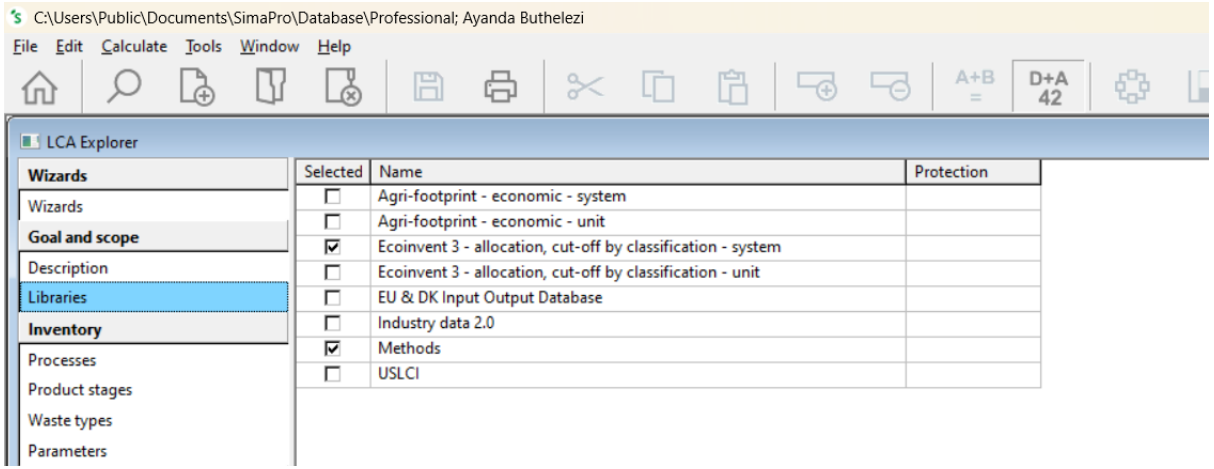

Figure E 2: SimaPro libraries (Libraries used in the current study selected)

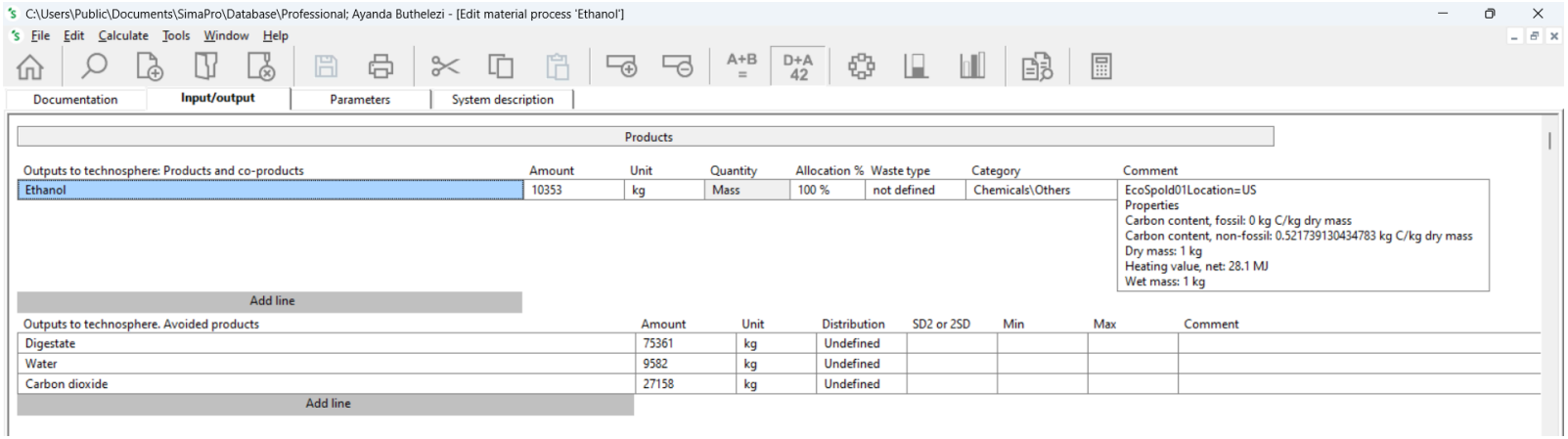

Figure E 3: Bioethanol production outputs

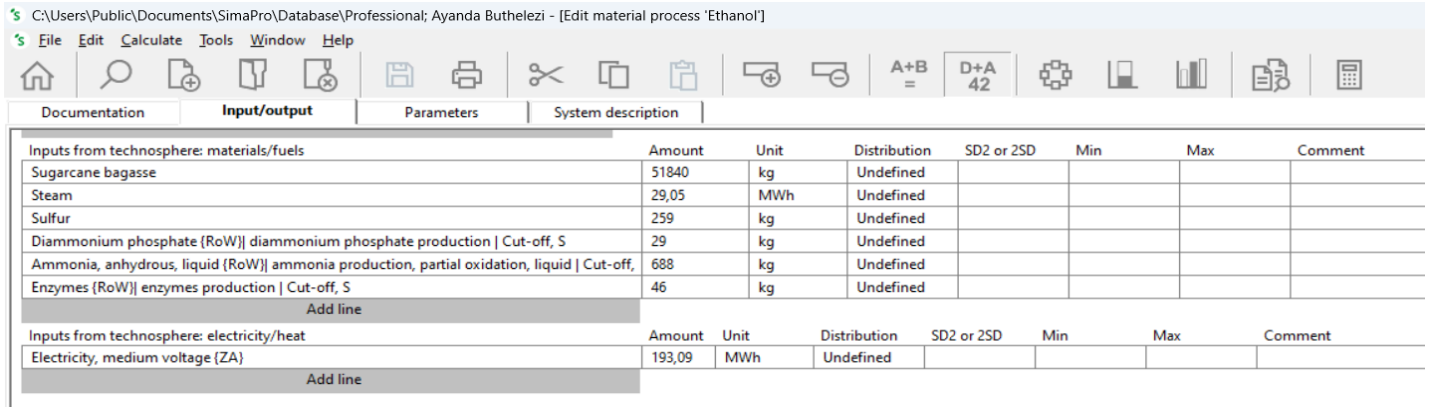

Figure E 4: Bioethanol production inputs

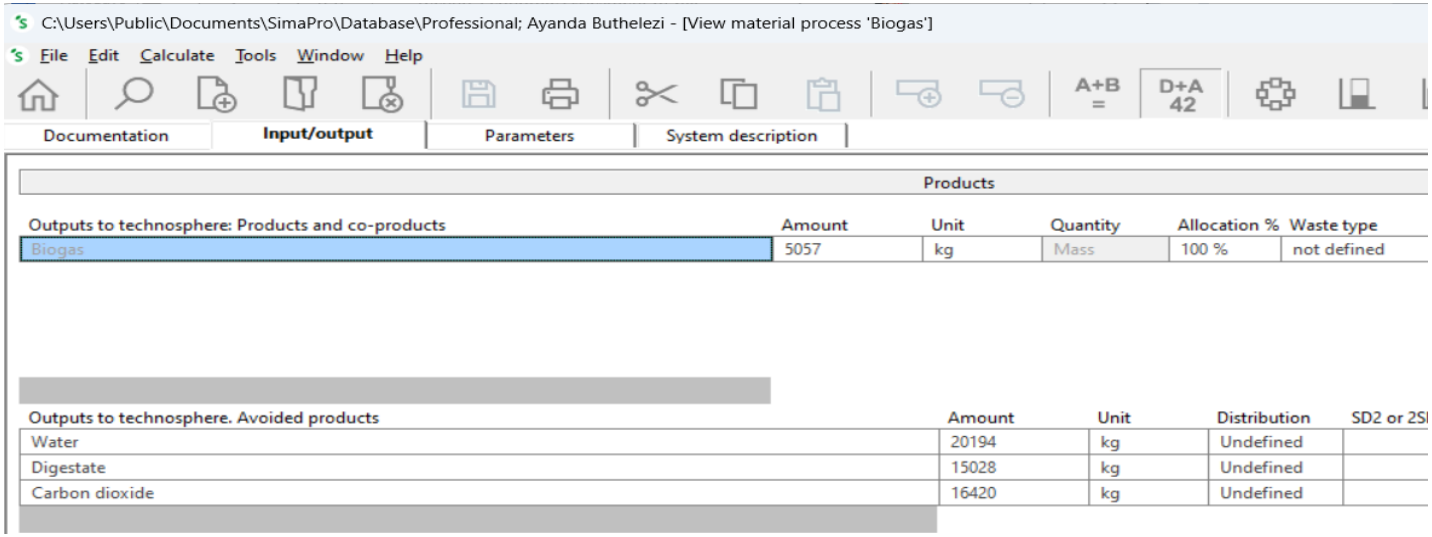

Figure E 5: Biogas production outputs

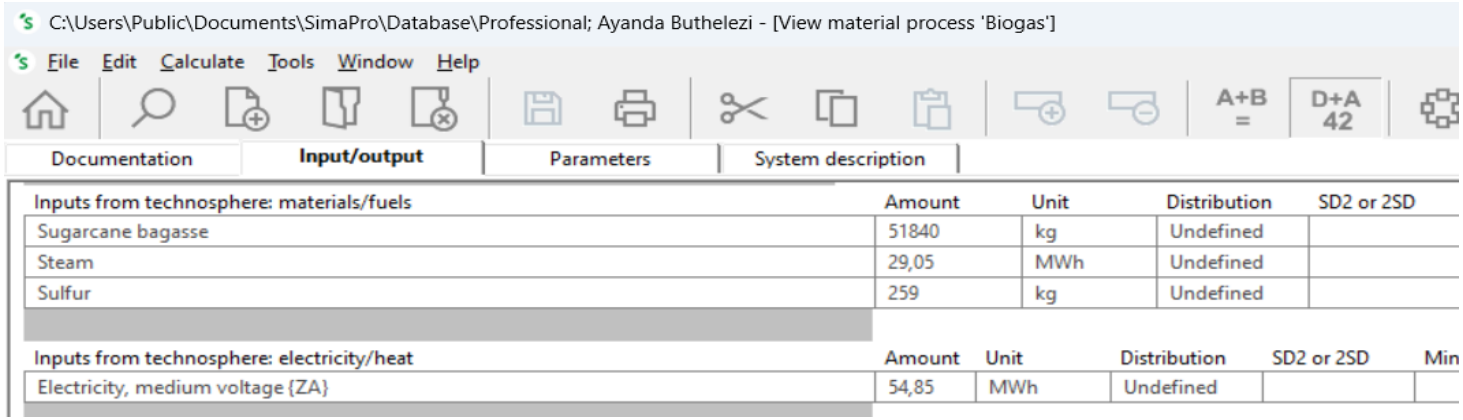

Figure E 6: Biogas production inputs

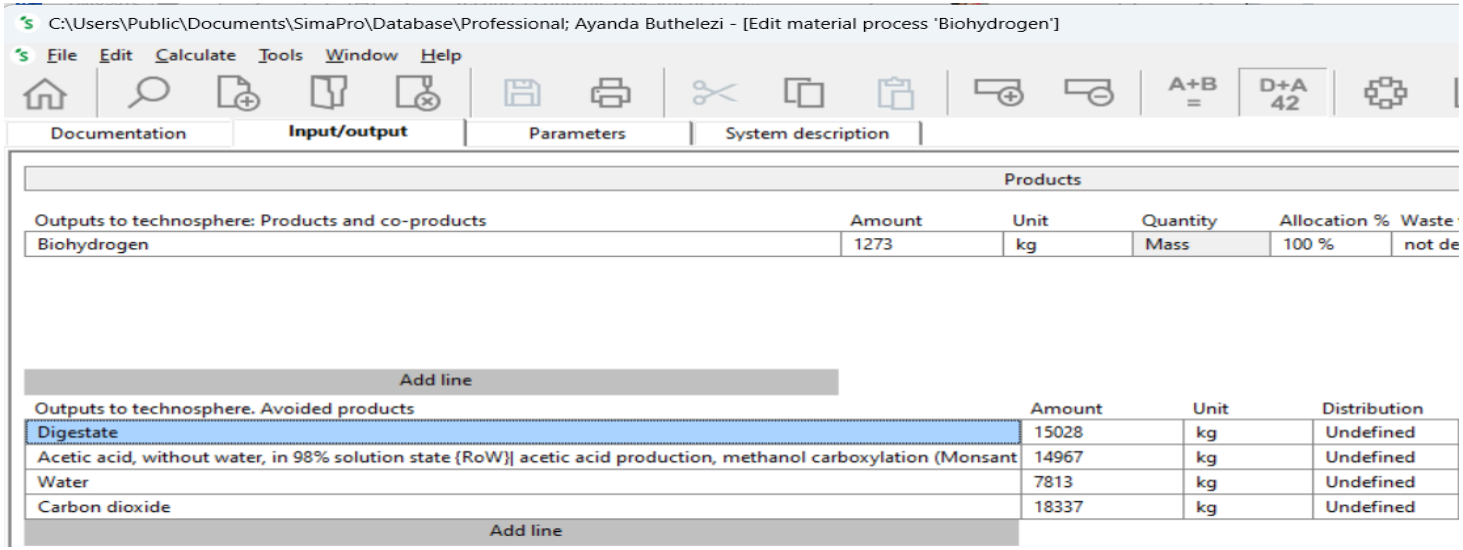

Figure E 7: Dark fermentation production outputs

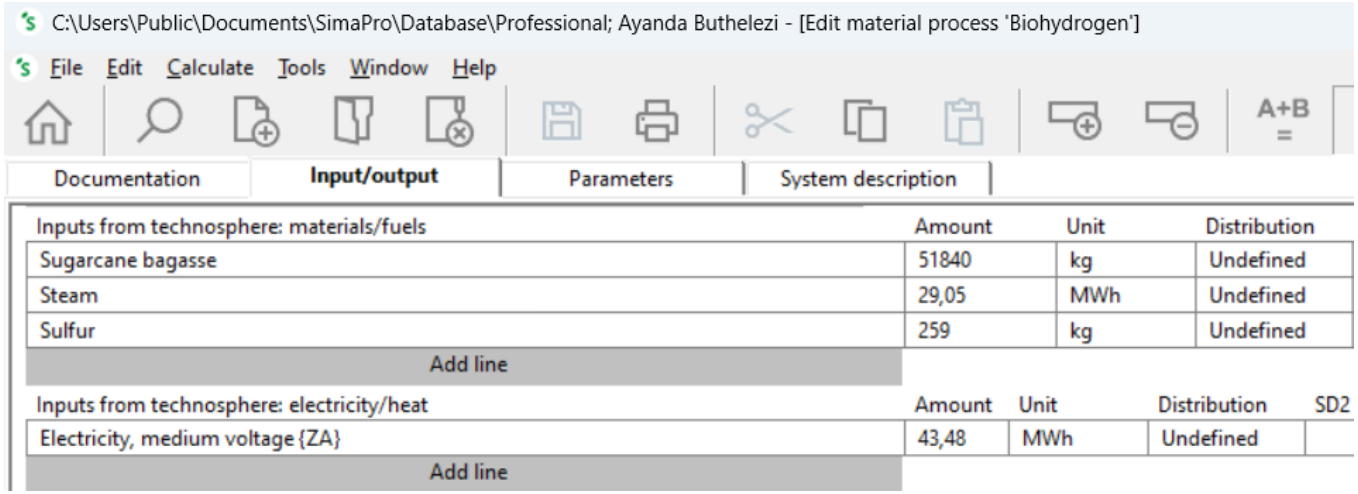

Figure E 8: Dark fermentation production inputs

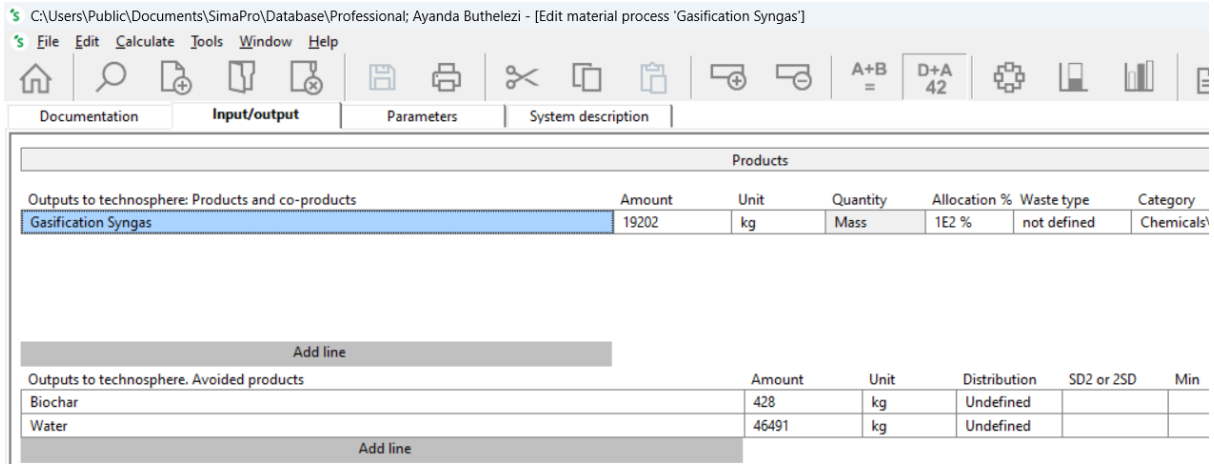

Figure E 9: Gasification outputs

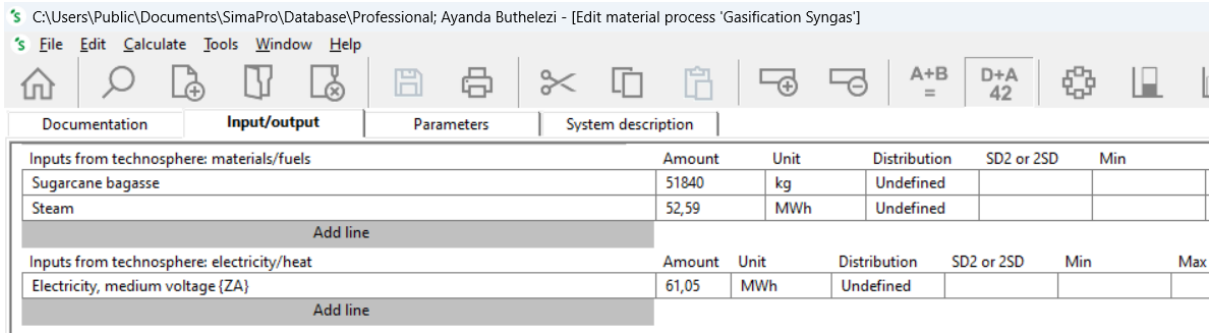

Figure E 10: Gasification inputs

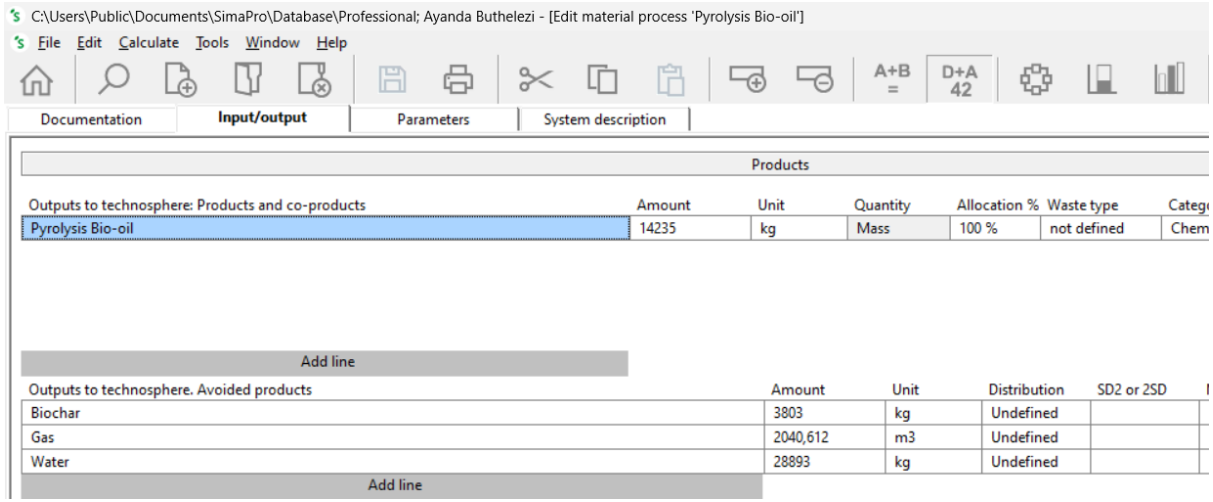

Figure E 11: Pyrolysis outputs

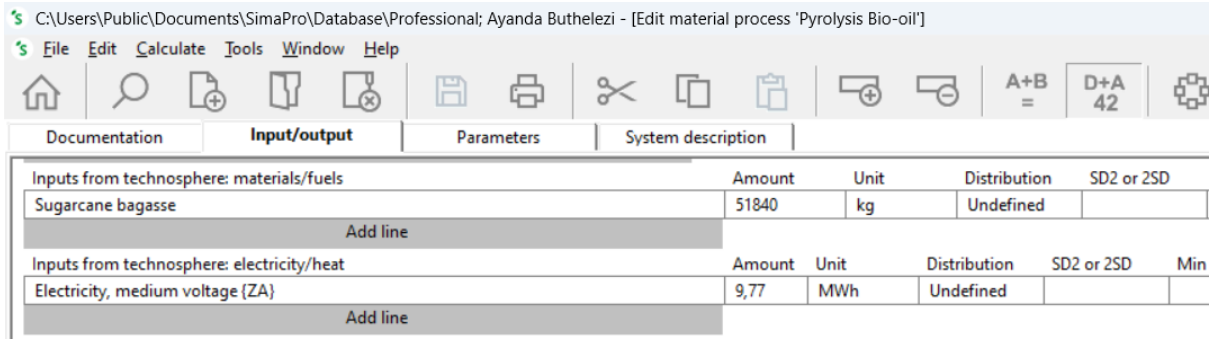

Figure E 12: Pyrolysis inputs

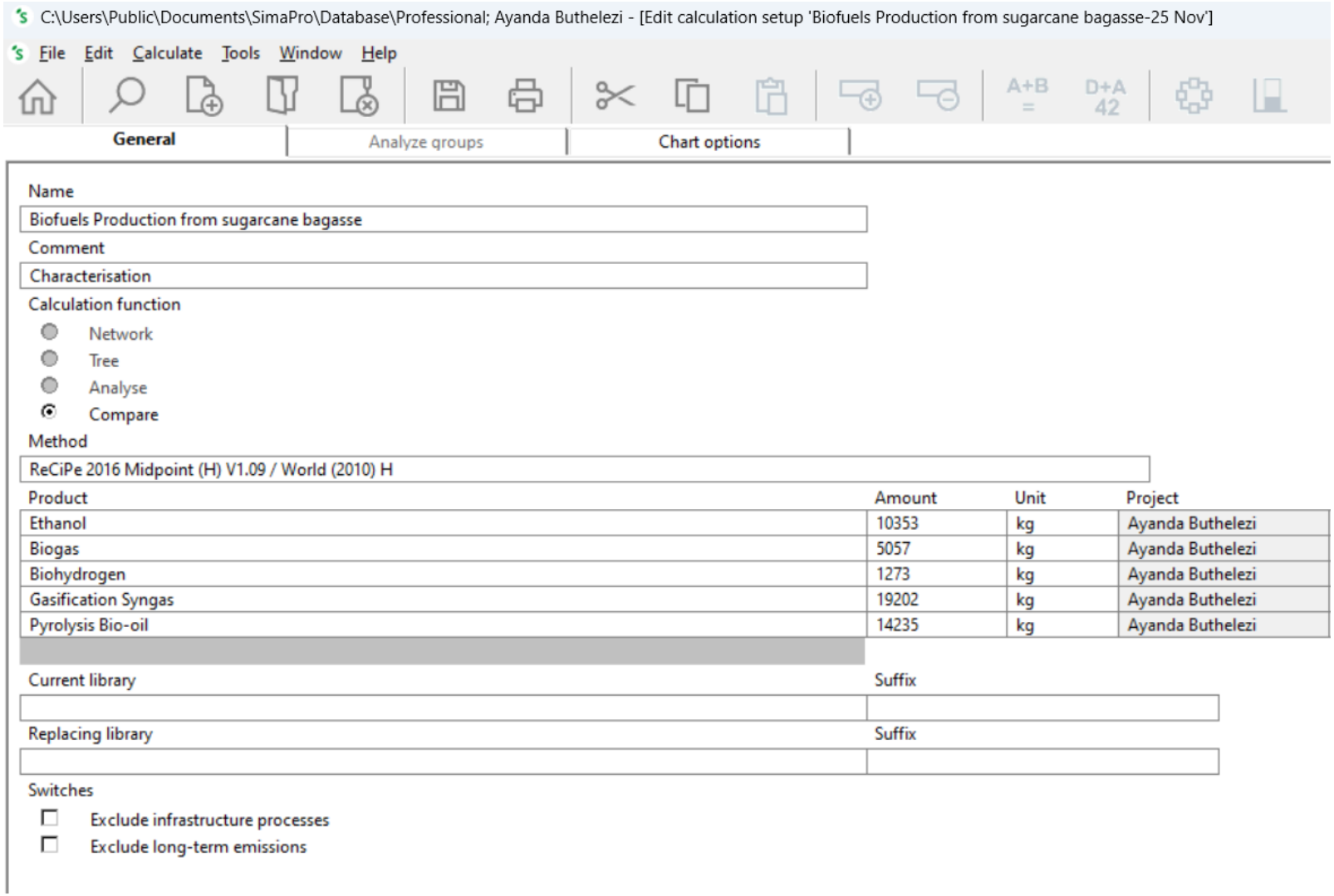

Figure E 13: Comparison using ReCipe2016 Midpoint (H)

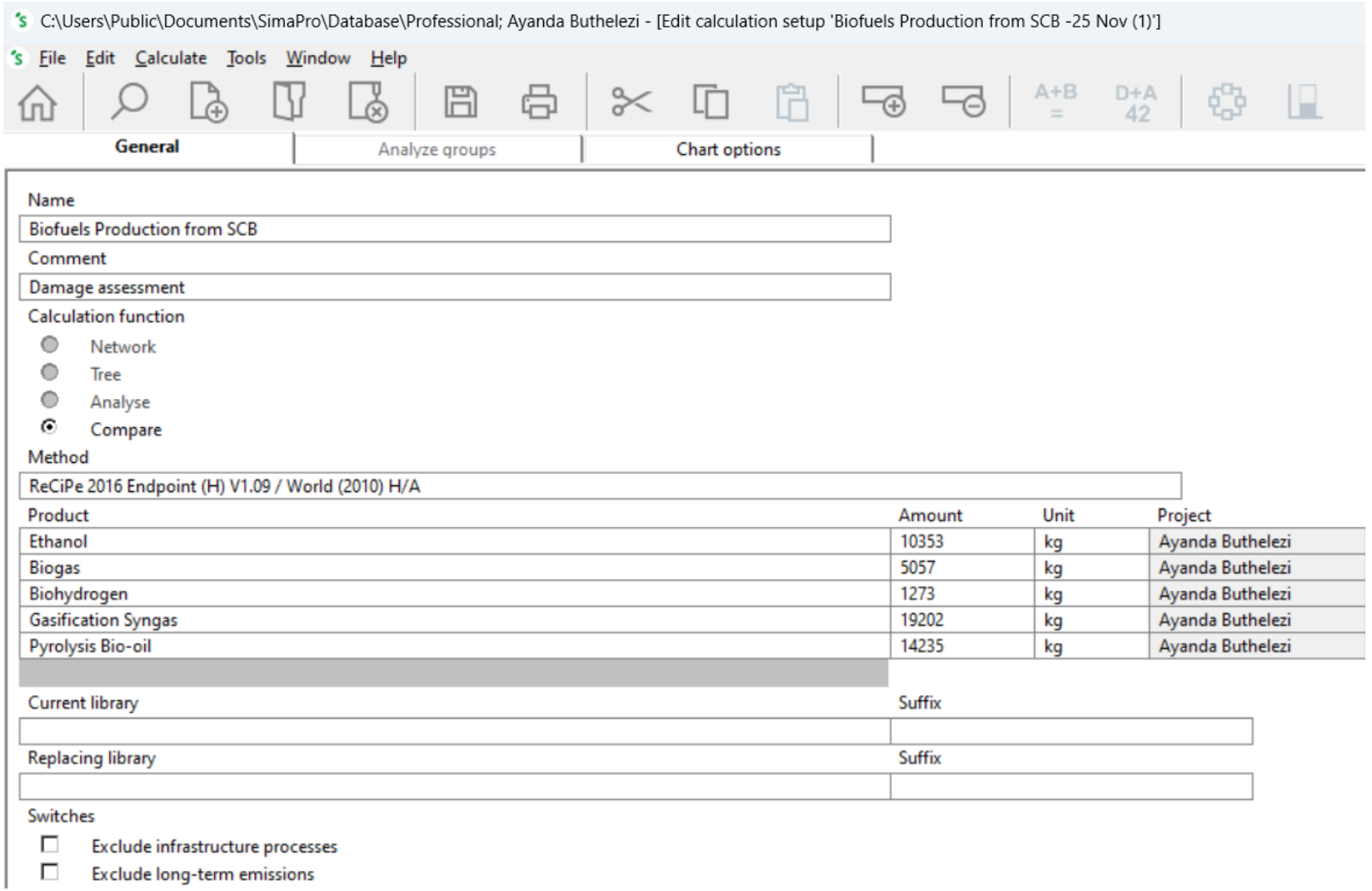

Figure E 14: Comparison using ReCipe2016 Endpoint (H)

Appendix F: Sample Calculations

1. Calculation of feedstock available for processing

Sugarcane crushing capacity=300 tonnes per hour, typical sugarcane crushing capacity in a sugar mill in South Africa

$$\text{Sugarcanebagasse capacity} = \frac{300\ \text{Te}}{\text{hour}} \times \frac{270\ \text{kg SCB}}{1\ \text{Te sugarcane}} = 81000\ \text{kg SCB/hr}$$ (Miranda *et al.* 2021)

36% is used for steam production (Moonsamy 2021).

Available sugarcane bagasse for biofuel production is as follows:

$$\text{SCB} = \frac{81000\ \text{kg SCB}}{\text{hr}} \times 0.64 = 51840\ \text{kg/hr SCB}$$

2. Estimation of sugarcane bagasse compositions

Component	Composition (mass %)
Cellulose	41.1
Hemicellulose	26.4
Lignin	21.7
Ashes	4
Extractive	6.8

Sugarcane bagasse leaving the dewatering mills has 50 wt.% moisture content.

Compositions used in simulations were calculated as follows:

$$\text{Water} = 50\%$$

$$\text{Cellulose} = 41.1 \times 0.5 = 20.55\%$$

$$\text{Hemicellulose} = 26.4 \times 0.5 = 13.2\%$$

$$\text{Lignin} = 21.7 \times 0.5 = 10.85\%$$

$$\text{Ashes} = 4 \times 0.5 = 2\%$$

$$\text{Cellulose} = 6.8 \times 0.5 = 3.4\%$$

3. Calculation of products yields

$$\text{Product yield} = \frac{\text{Mass of product(s)}}{\text{Mass of sugarcane bagasse}}$$

$$\text{Bioethanol Production} = \frac{\text{Mass Bioethanol}}{\text{Mass of sugarcane bagasse}} = \frac{10353}{51840} = 0.20$$

$$\text{Biogas Production} = \frac{\text{Mass of Methane}}{\text{Mass of sugarcane bagasse}} = \frac{5057}{51840} = 0.10$$

$$\text{Biohydrogen Production} = \frac{\text{Mass of Hydrogen}}{\text{Mass of sugarcane bagasse}} = \frac{1273}{51840} = 0.025$$

$$\text{Gasification} = \frac{\text{Mass of syngas} + \text{Mass of char}}{\text{Mass of sugarcane bagasse}} = \frac{19202 + 428}{51840} = 0.38$$

$$\text{Fast pyrolysis} = \frac{\text{Mass of bio} - \text{oil} + \text{Mass of syngas} + \text{Mass of char}}{\text{Mass of sugarcane bagasse}}$$

$$= \frac{14235 + 4908 + 3803}{51840} = 0.44$$

4. Economic assessment calculations

The same calculation procedure was used for all processes: Bioethanol production process will be used for sample calculations:

Estimation of Capital Expenditure (CAPEX)

Equipment cost from ASPEN PLUS

Total	**$**	**2 068 500.00**
Pretreatment	$	669 900.00
Enzyme Production	$	210 900.00
Fermentation and flashing	$	414 900.00
Ethanol Purification	$	772 800.00

$$\text{Total installed costs} = \$2068500$$

$$\text{Inside battery Limit (ISBL)} = \frac{\text{2024 CEPI}}{\text{2019 CEPI}} \times \text{Total installed costs} = \frac{800.7}{607.5} \times 2068500$$

$$= \$2\ 726\ 334.07$$

$$\text{Off} - \text{site battery limit(OSBL)} = \text{ISBL} \times 0.4 = \$2\ 726\ 334.07 \times 0.4 = \$1\ 090\ 533.63$$

$$\text{Engineering Costs (EC)} = (\text{ISBL} + \text{OSBL}) \times 0.1$$

$$= (\$2\ 726\ 334.07 + \$1\ 090\ 533.63) \times 0.1 = \$381\ 686.77$$

$$\text{Contingency Costs (CC)} = (\text{ISBL} + \text{OSBL}) \times 0.1$$

$$= (\$2\ 726\ 334.07 + \$1\ 090\ 533.63) \times 0.1 = \$381\ 686.77$$

Fixed Capital Investment (FCI)

$$= \text{engineering costs (EC)} + \text{contingency costs (CC)} + \text{off}$$

$$- \text{site plant costs (OSBL)} + \text{internal battery limit (ISBL)}$$

$$= \$2\ 726\ 334.07 + \$1\ 090\ 533.63 + \$381\ 686.77 + \$381\ 686.77$$

$$+ \$381\ 686.77$$

$$= \$8\ 397\ 108.95$$

$$\text{Working Capital (WC)} = (\text{ISBL} + \text{OSBL}) \times 0.15$$

$$= (\$2\ 726\ 334.07 + \$1\ 090\ 533.63) \times 0.15 = \$572\ 530.16$$

$$\text{Startup Costs (SUC)} = (\text{ISBL} + \text{OSBL}) \times 0.1 = (\$2\ 726\ 334.07 + \$1\ 090\ 533.63) \times 0.1$$

$$= \$381\ 686.77$$

$$\text{Capital Expenditure (CAPEX)} = \text{FCI} + \text{WC} + \text{SUC}$$

$$= \$8\ 397\ 108.95 + \$572\ 530.16 + \$381\ 686.77 = \$9\ 351\ 325.87$$

Estimation of Operating Expenses (OPEX)

Variable Costs

$$\text{Costs/year} = \text{Annual requirements} \times \text{price}$$

$$\text{Annual operating hours} = 5000 \text{ hours per year}$$

Material	Operating hours (hr/year)	Value (kg/hr)	Value (kg/yr)	Cost($/kg)	Cost ($)
Sugarcane bagasse	5000	51840	259200000	$ -	$ -
Sulphur	5000	259	1295000	$ 0.12	$ 151 515.00
Ammonia	5000	688	3440000	$ 0.54	$ 1 857 600.00
DAP	5000	29	145000	$ 0.55	$ 79 025.00
Microorganism	5000	46	230000	$ 17.00	$ 3 910 000.00
Air	5000	1233	6165000	$ 0.01	$ 50 518.98
Lower Pressure steam	5000	7212	36060000	$ 0.00	$ 110 704.20
Process Water	5000	60618	303090000	$ 0.00	$ 930 486.30
Cooling water	5000	8166806.808	56713936.17	$ 0.00	$ 174 111.78
Electricity	5000	98240.36046	491201802.3	$ 0.09	$ 42 243 355.00
			Variable operating costs		**$ 49 507 316.27**

Fixed Operating Costs

Labour

$$N_{OP} = (6.29 + 0.23\,N_{NP} + 31.7\,P^2)^{0.5} = (6.29 + 0.23\,(3) + 31.7\,(0)^2)^{0.5} = 2.50$$

$$\approx 3 \text{ operators per shift}$$

Assuming that the plant will be operating 24 hours with three 8-hour shifts per day

$$\text{Operators monthly labour costs} = \frac{\$529.41}{\text{month}} \times 3\frac{\text{operators}}{\text{shift}} \times 3\frac{\text{shifts}}{\text{day}} \times 30\frac{\text{days}}{\text{month}}$$

$$= \$142\,940.70$$

$$\text{Cost of Operating Labour (COL)} = \frac{\$142\,940.70}{\text{month}} \times \frac{5000\text{ h}}{\text{year}} \times \frac{\text{month}}{730\text{ h}} = \$992\,643.75$$

$$\text{Supervision cost} = 0.25 \times \text{COL} = 0.25 \times \$992\,643.75 = \$248\,160.94$$

$$\text{Direct overhead} = 0.4(\text{Cost of Operating labour} + \text{Supervision cost})$$

$$= 0.4(\$992\,643.75 + \$248\,160.94) = \$496\,321.88$$

$$\text{Maintenance costs} = 4\%(\text{ISBL} + \text{OSBL}) = 4\% \times \$3\,816\,867.70$$

$$= \$109\,053.36$$

$$\text{Property taxes and insurance} = 4\% \times \$2\,726\,334.07 = \$54\,526.68$$

General plant overhead

$$= 65\% \times (\text{Labour costs} + \text{Supervision costs} + \text{Direct costs} + \text{Maintenance costs})$$

$$= 65\% \times (\$992\,643.75 + \$248\,160.94 + \$496\,321.88 + \$54\,526.68)$$

$$= \$1\,200\,016.95$$

$$\text{Environmental charges} = 1\%(\text{ISBL} + \text{OSBL}) = 1\%(\ \$3\ 816\ 867.70\ )$$
$$= \ \$38\ 168.68$$

$$\text{Fixed Costs} = \text{Cost of Operating Labour} + \text{Supervision} + \text{Direct overhead}$$
$$+ \text{Maintenance} + \text{Property taxes and insurance} + \text{Land rent}$$
$$+ \text{General plant overhead} + \text{Environmental charges}$$
$$= \$992\ 643.75 + \$248\ 160.94 + \ \$496\ 321.88 + \ \$109\ 053.36$$
$$+ \ \$54\ 526.68 + \ \$1\ 200\ 016.95 + \ \$38\ 168.68 = \ \$3\ 138\ 892.24$$

$$\text{Operating Expenses (OPEX)} = \text{Variable operating costs} + \text{Fixed costs}$$

$$= \ \$49\ 507\ 316.27 \ + \$3\ 138\ 892.24 = \ \$52\ 646\ 208.50$$

Total Revenue

$$\text{Total revenue} = \text{Amount of final product} \times \text{Selling price}$$
$$= 10353\ \text{kg}\frac{\text{ethanol}}{\text{hr}} \times \frac{5000\text{hr}}{\text{year}} \times \frac{\$0.88}{\text{kg}} = \ \$45\ 466\ 596.96$$

Gross Profit

$$\text{Gross Profit} = \text{Total revenue} - \text{OPEX} = \ \$45\ 466\ 596.96 - \ \$52\ 646\ 208.50$$
$$= \ \$ - 7\ 179\ 611.54$$

Discounted cash flow analysis

$$\text{DCF}_n = \frac{\text{CF}_n}{(1 + \text{i})^n}$$

It is assumed that the plant started with construction in 2023 to 2025 and will start operating in 2025. The first two years are assumed to be planning and construction phases.

For the year 2025:

$$\text{Depreciation expense (\$)} = \text{Gross Profit} \times \text{Depreciation rate}$$
$$= \$ - 7\ 179\ 611.54\ \times 20\% = \ \$ - 1\ 435\ 922.31$$

$$\text{Taxable income (\$)} = \text{Gross Profit} - \text{Depreciation expense}$$
$$= \$ - 7\,179\,611.54 - \$ - 1\,435\,922.31 = \$ - 5743689.23$$

$$\text{Tax paid (\$)} = \text{Taxable income (\$)} \times \text{Tax rate} = \$ - 5743689.23 \times 28\%$$
$$= \$ - 1608232.99$$

$$\text{Net Cash flow (\$)} = \text{Gross Profit (\$)} - \text{Tax paid (\$)}$$
$$= \$ - 7\,179\,611.54 - \$ - 1608232.99 = \$ - 5571378.56$$

$$\text{DCF}_{2025} = \frac{\text{CF}_\text{n}}{(1+\text{i})^\text{n}} = \frac{\$ - 5571378.56}{(1+0.12)^1} = \$ - 4974445.14$$

The same procedure is followed to calculate the discounted flow analysis for the lifetime of the project (25 years).

Appendix G: Model Files

All Aspen Plus simulation files, Aspen Process Economic Analyzer (APEA) costing files, and SimaPro life cycle assessment project files used in this study have been archived and stored in the Durban University of Technology (DUT) OneDrive account of the author. These files are available for verification and can be accessed using the following link:

C:\Users\Ayand\OneDrive - Durban University of Technology\MEng 2021\TEA of biofuel production from Sugarcane bagasse\Thesis draft