

**SIMULATION, OPTIMIZATION, AND ECONOMIC ANALYSIS OF
BIOHYDROGEN PRODUCTION USING FOOD WASTES FROM THE HOTEL
INDUSTRY IN NAIROBI CITY COUNTY, KENYA**

EMILY MACHUMA MUCHELE


J104/CTY/PT/20419/2020

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE AWARD OF THE DEGREE OF MASTER OF
SCIENCE (RENEWABLE ENERGY TECHNOLOGY) IN THE SCHOOL OF
ENGINEERING AND ARCHITECTURE OF KENYATTA UNIVERSITY.**

DECEMBER, 2025

DECLARATION

I declare that this is my original work and has not been presented for a degree in any other University.

Signature.......... Date..... 28 / 11 / 2025

Emily M. Muchele


REG. No: J104 / CTY / PT / 20419 / 2020

The Thesis has been submitted for examination with our approval as the University Supervisors

Signature.......... Date..... 28 / 11 / 2025

DR. BOOKER OSODO, PhD

Department of Energy, Gas and Petroleum Engineering, Kenyatta University.

Signature.......... Date..... 01 / 12 / 2025

DR. ISAIHAH OMOSA, PhD

Department of Civil Engineering, Kenyatta University.

DEDICATION

This work is dedicated to my family.

ACKNOWLEDGEMENT

I appreciate my supervisors and advisors, Dr. Booker Osodo, Dr. Isaiah Omosa, and Dr. Emmanuel Yeri, for their resolute support and conscious critiques throughout my research journey. Their strong commitment to academic excellence, cautious attention to detail, constructive criticism, and integral suggestions enhanced the quality of this thesis.

I also extend my gratitude to the Chairman, faculty, and staff in the Department of Energy, Gas, and Petroleum of Kenyatta University, whose support has been invaluable. I would also like to acknowledge my classmates for their stimulating engagements and discussions that inspired me throughout my academic journey. Their collective intelligence and encouragement were the foundation of my research experience.

Finally, I want to express my sincere thanks to the technical staff, whose expertise in managing Chemistry and Science Zone laboratory equipment was crucial for my experiments. Their patience and readiness to assist at all times had a profound impact on the achievement of the first objective of this work.

TABLE OF CONTENTS

DECLARATION	i
DEDICATION	ii
ACKNOWLEDGEMENT	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	ix
DEFINITION OF TERMS	xii
ABSTRACT	xiii
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background	1
1.2 Problem statement.....	2
1.3 Justification of the study	3
1.4 Research objectives.....	4
1.4.1 General Objective.....	4
1.4.2 Specific Objectives.....	4
1.5 Research questions	4
1.6 Significance of the study.....	5
1.7 Scope and limitation of the study.....	5
1.8 Theoretical and Conceptual Framework.....	6
1.8.1 Theoretical Framework	6
1.8.2 The Conceptual Framework	7
CHAPTER TWO	8
2 LITERATURE REVIEW	8
2.1 Theoretical background.....	8
2.1.1 Biomass classification	8
2.1.2 Biomass Conversion.....	8
2.1.3 Biomass gasification.....	9
2.1.4 Characterization techniques	13
2.1.5 Modelling	13
2.1.6 Project Economic Analysis	19
2.2 Summary of related studies.....	19

2.3 Identified research gap	23
CHAPTER THREE.....	24
3 MATERIALS AND METHODS	24
3.1 Study Area.....	24
3.2 Determination of the physical and biochemical characteristics.....	25
3.2.1 Collection and Preparation of Substrate for Characterization.....	25
3.2.2 Analysis	26
3.2.3 ANOVA for proximate and ultimate analysis of samples.....	32
3.3 Simulation and Validation using Aspen Plus.....	33
3.3.1 Process Simulation Model Development	33
3.3.2 Model Flow Sheet Description.....	34
3.3.3 Simulation Procedure	35
3.3.4 Model assumptions.....	39
3.3.5 Sensitivity Analysis Procedure.....	40
3.3.6 Model Validation.....	40
3.4 Response Surface Methodology (RSM) analysis and optimization procedure.....	40
3.4.1 Analysis of Variance	41
3.5 Economic Analysis	41
3.5.1 Net Present Value (NPV)	43
3.5.2 Internal Rate of Return (IRR).....	43
3.5.3 Simple Payback Period (SPBP).....	43
3.5.4 Discounted Payback Period (DPBP)	44
3.5.5 Profitability Index (PI)	44
3.5.6 Economic Analysis assumptions	45
CHAPTER FOUR	46
4 RESULTS AND DISCUSSION	46
4.1 Physical and Biochemical Characteristics of the Sampled Food Wastes	46
4.1.1 Moisture Content (MC)	46
4.1.2 Total Solids (TS) and Volatile Solids (VS).....	47
4.1.3 Ash and Fixed Carbon.....	48
4.1.4 Nitrogen and Total Organic Carbon (TOC)	50
4.1.5 Carbon to Nitrogen (C/N) ratio	51
4.1.6 Crude proteins and lipids.....	53

4.1.7 Potassium, Sodium, Calcium, and Phosphorus	54
4.1.8 Analysis of Variance (ANOVA) and model Summary for characterization results	57
4.2 Simulation of Biohydrogen Production results	60
4.2.1 Model validation results	60
4.2.2 Influence of temperature	62
4.2.3 Influence of air-to-fuel ratio	64
4.2.4 Influence of steam-to-biomass ratio	66
4.3 Optimization using Response Surface Methodology (RSM).....	67
4.3.1 Regression Equation in Uncoded Units.....	67
4.3.2 Linear effect of process variables.....	68
4.3.3 Analysis of Variance and Model Summary	69
4.3.4 Decision variables' effect on Hydrogen mole fraction yield	71
4.3.5 Interrelationship of variables on hydrogen mole fraction and yield	72
4.3.6 Parameter Optimization.....	74
4.4 Findings of Economic Analysis	75
CHAPTER FIVE	78
5 CONCLUSIONS AND RECOMMENDATIONS	78
5.1 Conclusions.....	78
5.2 Recommendations.....	79
REFERENCES	80
APPENDICES.....	110
Appendix A: Photos taken during Characterization of Food Wastes.	110
Appendix B: Sample weights and pH as recorded during experiments	113
Appendix C: Standard and sample data versus charts used in compositional determination	114
Appendix D: Food waste Characterization results.....	118
Appendix E: Food waste characterization results compared with other related studies	119
Appendix F: ANOVA	120
Appendix G: Publication.....	122

Appendix H: Research Approval from Graduate School.....123
Appendix I: Research Authorization from Graduate School124
Appendix J: Research License from NACOSTI.....125

LIST OF TABLES

Table 2-1: Summary of other related studies.....	22
Table 3-1: Definition of blocks and their conditions.....	37
Table 3-2: Model feed stream and their operating conditions	39
Table 3-3: Equipment and material cost estimates of the system.....	42
Table 4-1: ANOVA and model summary of food waste characterization results	58
Table 4-2: Comparison between experimental and simulated results	62
Table 4-3: ANOVA and Model Summary results	70

LIST OF FIGURES

Figure 1-1: Schematic diagram of the Theoretical and Conceptual framework.....	6
Figure 2-1: Illustration of different routes of bio-hydrogen production(Kuppam et al., 2017).....	9
Figure 2-2: Schematic step for biohydrogen production (Babatabar & Saidi, 2021).....	14
Figure 2-3: Aspen Plus flow process simulation (Mohammadidoust & Omidvar, 2020)	15
Figure 2-4: Sequential steps in optimization process using RSM (de Oliveira Filho et al., 2018).....	16
Figure 2-5: Example of an optimized system using three factors (Alavi-Borazjani et al., 2021).....	17
Figure 3-1: Nairobi County location from Map data 2025.....	24
Figure 3-2 : Food waste gasification model flow sheet for hydrogen generation in Aspen Plus.....	36
Figure 4-1: Moisture content results.....	46
Figure 4-2: Total and Volatile results.....	47
Figure 4-3: Nitrogen and Total Organic Carbon results.....	50
Figure 4-4: Carbon to Nitrogen ratio results.....	52
Figure 4-5: Crude proteins and lipid results	54
Figure 4-6: Potassium, Sodium, Calcium, and Phosphorus results	55
Figure 4-7: Comparison between Aspen Plus simulation Model and experimental results at different MCs and A/Fs	61
Figure 4-8: Influence of Temperature on (a) hydrogen flow rate and yield, (b) Syngas Composition.....	63
Figure 4-9: Influence of air-to-fuel ratio on (a) hydrogen flow rate, yield, (b) syngas Composition	65
Figure 4-10: Influence of Steam to Biomass ratio on (a) hydrogen flow rate, yield and (b) Syngas Composition	66
Figure 4-11: Pareto Chart with a standardized effect	68
Figure 4-12: Effect of variables on Hydrogen yield.....	71
Figure 4-13: Contour and surface plots of the system holding (a-b) A/F at 1.15 (c-d) temperature at 750 °C , and (e-f) SBR at 1.75	72

Figure 4-14: Contour and surface plots of the system holding (a-b) A/F at 1.15, (c-d) temperature at 750 °C and (e-f) SBR at 1.75	74
Figure 4-15: Optimal Hydrogen yield at maximum desirability of 1.0.....	75
Figure 7-1: 1-4.Food waste collection &-sampling, 5.Wet sample homogenized, 6.pH Measurement, 7-8. Oven @105 °C, 9.Muffle furnace 10. Ash weighing.....	110
Figure 7-2: 11.Sample weighing, 12. Empty thimble, 13.Thimble + sample, 14.Soxhlet extractor in operation, 15. Flask + Extracted lipid, 16-17 Sample digestion for Nitrogen and protein, 18 Kjeldahl Protein Apparatus, 19. Distillation, 20. Titration	111
Figure 7-3: 21-30-Potassium and sodium determination using Flame Photometer. 31-38. Phosphorus and sulfur determination using U-V Spectrophotometer. 39. Potassium dichromate for Total Organic Carbon (TOC) determination and 40. Standard chart from U-V for TOC.....	112

ACRONYMS AND ABBREVIATIONS

ANOVA –	Analysis of Variance
CCD –	Central Composite Design
COD –	Chemical Oxygen Demand
DF-	Dark Fermentation
DoE-	Design of Experiment
EF-	Electro Fermentation
EEM-	Energy Efficiency Measures
EGT-	Energy Generation Technologies
F&B-	Food and Beverages
FW-	Food Waste
GHG-	Green House Gas
HRT-	Hydraulic Retention Time
HES-	Hotel Energy Solutions
HY-	Hydrogen Yield
MEC-	Microbial Electrolysis
MC -	Moisture Content
PF-	Photo Fermentation
RES -	Renewable Energy Sources
RSM -	Response Surface Methodology
SHPR-	Specific Hydrogen Production Rate
SBR-	Steam to biomass ratio
IRENA -	International Renewable Energy Agency
ICP-OES-	Inductively Coupled Plasma Optical Emission Spectroscopy
TVS-	Total Volatile Solids
VFA-	Volatile Fatty Acids
WtE-	Waste to Energy

DEFINITION OF TERMS

Bioenergy- Renewable energy produced by living organisms(Gómez-Marín & Bridgwater, 2021; Hosseinzadeh-Bandbafha et al., 2021).

Bio hydrogen- Hydrogen produced from bio-resources like biomass (Akhlaghi & Najafpour-Darzi, 2020).

Methane (CH₄) -A chemical compound with one carbon atom bonded to four hydrogen atoms. A greenhouse gas after carbon dioxide (CO₂) is accelerated by human activity to enhance climate change impacts (Polag & Keppler, 2019; Saunois et al., 2020).

Food waste – Discarded Food of good quality that can be consumed or converted into another useful final product (do Carmo Stangherlin & De Barcellos, 2018; Giordano et al., 2018; Hartikainen et al., 2018).

Food waste footprint- Measure of the amount of food lost and its environmental impacts along the supply chain. The longer the chain, the higher the food waste footprint (Cakar et al., 2020; Tonini et al., 2018).

Carbon footprint- Total amount of greenhouse gas emitted throughout the lifecycle of food products expressed in kilograms of CO₂ or its equivalents (Lenzen et al., 2018; Z. Li et al., 2021).

Simulation model that imitates the operation of an existing or proposed system, enhancing decision-making process by testing it under various circumstances (Manurung, 2019; Pobirchenko et al., 2019).

Optimization- Process of making something e.g. a system, design, or decision to function perfectly (Gill et al., 2019).

Hotel-A facility that provides accommodation, food and drinks for visitors who could be looking for recreation, entertainment or meetings (Onyango & Ngahu, 2018).

ABSTRACT

Disposed food waste produces greenhouse gases e.g., methane and carbon dioxide in landfills, destroying the environment through climate change and global warming. In the hotel industry, the serving-stage foods which include plate wastes (leftovers) and display (buffet) wastes prepared for consumption but never consumed, end up in waste bins that fill the landfills. About 230 kg of food wastes were collected from 21 hotels in Nairobi City County, Kenya, and characterized in the present study. Using characterization data, the study simulated and optimized bio-hydrogen production from food wastes. A numerical simulation model of air gasification of food wastes integrated with syngas conditioning for hydrogen-rich syngas production by use of Aspen Plus was developed. The influence of gasifier temperature, air-to-fuel ratio (A/F), and steam-to-biomass ratio (SBR) on hydrogen flow rate, yield, and syngas composition was studied. The combined effect of temperature, A/F, and SBR was studied using Response Surface Methodology (RSM) to establish the optimal points for maximum hydrogen production. Furthermore, an economic analysis based on the optimum hydrogen yield was computed. The RSM analysis indicated an optimal performance at a temperature of 889.39 °C, A/F of 0.5, and SBR of 2.87 with a corresponding maximum hydrogen yield of 12.99 %. With a positive net present value (NPV) of \$8741, a profitability index (PI) of 1.28, and an internal rate of return (IRR) of 20 %, the cost of investment would be recovered in 4.15 years. These economic results may vary significantly due to the advancement of technologies and changing local economies. The accuracy of the proposed model could be enhanced by incorporating hydrogen storage and hydrodynamics in the future. These results suggest that the raw syngas produced could be cleaned up by running through the cleaning chamber that separates various components and harmful impurities like mercury, sulphur, and unconverted carbon. The carbon footprint of hotels can be measured since it is possible to pull out carbon dioxide and either store it underground or use it for methanol or ammonia production. Hotels can embrace waste-to-energy technologies and zero waste systems to avoid to save on energy costs avoid environmental pollution. It is evident from this study that research on integrated biohydrogen production technologies using different wastes can be commercially explored for the hotel industry.

CHAPTER ONE

INTRODUCTION

1.1 Background

Hydrogen has to be at the center point of any sustainable energy project if fossil fuels are to be substituted from now on (Ampah et al., 2021). The potential of biohydrogen production and its acceptance in industries relies on the availability of biomass, the principal energy source in the universe, after fossil fuels (Kombe et al., 2022). The hotel industry generates significant carbon dioxide (CO₂) emissions during the production, transportation, and handling of food. 45% of food wastage in the hotel industry is through food preparation and production processes, followed by food left on customer plates at 34% while 21% of food spoilage is through poor storage (Filimonau & Sulyok, 2021; Giri, 2021). Generally, decomposed foodstuffs share a common characteristic: they are biogenic and emit methane, carbon dioxide, and nitrous oxide which are significant greenhouse gases with consequential carbon, water, and food wastage footprints (Chavan et al., 2022; Wang et al., 2022).

Developing Countries like Kenya, require large quantities of food for consumption, especially in densely populated urban areas like Nairobi. The high demand for food results in purchasing or preparing too much. If prepared food is not consumed, the partially used food or leftovers will account for the food waste generation (Filimonau & Sulyok, 2021). The environmental pollution challenges associated with this create devastating climate change effects (Dilkes-Hoffman et al., 2018; Mahmudul et al., 2022). Food Waste decomposes in landfills, causing massive layers of organic waste that produce heat-trapping greenhouse gases (GHG) like methane, water vapor, carbon dioxide, nitrous oxide, chlorofluorocarbons, and ozone that worsen the climate change crisis (Dilkes-Hoffman et al., 2018; Mahmudul et al., 2022; Zeng et al., 2022). The emissions of these gases result in climate change which causes floods, drought, food shortage, water scarcity, diseases, and others (Hermans & McLeman, 2021; Javadinejad et al., 2021; Zeng et al., 2022), thereby requiring preventive measures to be established (Carpio-Aguilar et al., 2019; Graham-Rowe et al., 2019; Lieber et al., 2022). Substantial amounts of food wastes that are discarded yearly from food industries can be thermo-chemically or biologically converted into energy.

Since gasification is a complex process, modeling is advisable to appreciate and interpret its characteristics and study the effects of various parameters on its performance. This is achieved by commercially available computer-based simulation and modeling software like Aspen Plus (Ranjan et al., 2023), Aspen Hysys (Kartal et al., 2022), Fluent (Rao & Barman, 2023) and Chemkin (Wang et al., 2022). Literature indicates that Aspen Plus is popularly used for the simulation of gasification processes due to its pre-installed library model for calculating the characteristics of solids as compared to other software. Furthermore, numerical calculations are easily performed by a FORTRAN code (an imperative programming language) that simplifies numerical computations and customizations (Kombe et al., 2022). The food waste in this study is simulated in Aspen Plus and modelled as biomass during the gasification processes for hydrogen production. Comparatively, Ramzan et al., (2011) designed a simulation model for the gasification of municipal solid, food, and poultry waste. To achieve the best results, several authors integrated the gasification model and simulation process with Response Surface Methodology (RSM) for easier identification of optimum points. RSM is a numerical device with comprehensive engineering executions where synchronized optimization of several responses is indispensable (Lamidi et al., 2022). The current study not only characterizes, but also simulates, optimizes, and economically analyzes the bio-hydrogen production process using food wastes from the hotel industry

1.2 Problem statement

The high volume of food waste generated in hotels in Nairobi City County poses significant energy and environmental management challenges. The improper disposal of food wastes contributes to greenhouse gas emissions, pollution, and energy inefficiency while also representing a missed opportunity for renewable energy production. Inadequate waste segregation and collection points allow food waste to be mixed with other waste streams, making it difficult to recover and process energy production from it. It is important to note that ineffective food waste-to-energy conversion systems in hotels exacerbates not only energy scarcity, but also environmental degradation. This is enhanced by limited awareness of hotel management hindering the adoption and implementation of waste -to-energy technologies. Due to lack of technical expertise, it is perceived that the installation and maintenance of food waste-to-energy systems are cost-prohibitive.

Additionally, minimal availability of information on the specific biochemical composition of the ‘mixture’ of food wastes makes it difficult to process some useful end products. The physical and biochemical characteristics of food waste are influenced by many factors. Their degradation rate and biological composition affect the quality and quantity of the end product. For example, food waste consisting of rice and potatoes could contain starch while proteins and lipids (fats/oils) could be extracted from fish, meat, and eggs. It consumes time and resources to carry out tedious experiments on food wasted in hotels since the composition keeps changing (Karthikeyan et al., 2018; Slopicka et al., 2022).

The operation of a system cannot be visualized, and/or clearly demonstrated to gauge the ability or inability of the system to produce bio-hydrogen without simulation. There are also numerous challenges associated with testing the optimum points of the system using tedious, time-consuming, and resource-intensive experiments. In addition, it is difficult to make financial decisions on projects without economic analysis. This research, therefore, will give sufficient information on the possibility of food waste conversion to biohydrogen.

1.3 Justification of the study

The availability of information about the physical and biochemical composition of food waste managed waste generation in hotels. Characterization of food waste established parameters that informed the manufacturing industry on different raw materials for other affordable and useful products in the market, promoting reduce, reuse and recycle waste management practices. During this era of a circular economy, minimal landfilling reduces greenhouse gases that contribute to climate change. In addition, Waste-to-Energy (WtE) practices by hotels enhance renewable energy technology utilization consequently reducing energy demand to the grid, as well as minimizing energy bills /costs.

Simulation envisioned the operation of the system and demonstrated its ability to achieve its performance objectives. Therefore, safety risks associated with product complexities in terms of ignition, flammability, explosions, and technological uncertainty were avoided. The numerous challenges associated with testing the optimality of the system

using tedious, time-consuming, and resource-intensive experiments were also mitigated. The simulation explored ‘what if’ questions and scenarios without having to experiment on the system itself. This saved energy, human and financial resources. Optimization guided on the best combination of variables that gave the highest yield of hydrogen allowing biomimicry of the operation of the system.

An economic analysis addressed stakeholder reservations regarding the viability, acceptability, and sustainability of the project. Enhanced decision-making process especially in public investments increases transparency and accountability. Sufficient information, proper financial planning, budgeting, and analysis help in the implementation of projects leading to sustainably improved welfare of the beneficiaries.

1.4 Research objectives

1.4.1 General Objective

To simulate, optimize, and economically analyze bio-hydrogen production from food wastes generated by the hotel industry in Nairobi City County, Kenya

1.4.2 Specific Objectives

The specific objectives of the study will be:

1. To determine the physical and biochemical characteristics of sampled food wastes from hotels in Nairobi City County, Kenya.
2. To simulate biohydrogen production from food wastes obtained from hotels.
3. To optimize biohydrogen production from food wastes with respect to Temperature, air-to-fuel ratio, and steam-to-biomass ratio.
4. To carry out an economic analysis of the bio-hydrogen production process.

1.5 Research questions

1. What are the physical and biochemical characteristics of food waste in hotels in Nairobi?
2. How can food waste from the hotel industry produce biohydrogen through simulation using Aspen Plus Software?

3. What is the optimal combination of temperature, steam-to-biomass, and air-to-fuel ratio for maximum biohydrogen production?
4. How can the economic viability of a bio hydrogen production process be assessed using NPV, IRR, Payback period and Profitability Index in Microsoft Excel software?

1.6 Significance of the study

This study will address waste management issues not only in hotels but also in urban areas, hence contributing to the efforts to minimize environmental pollution. Useful food waste products will also be readily available in the market reducing their costs. During this era of climate change crisis, advanced knowledge of waste-to-energy technologies is key. This research will undertake simulation and optimization of biohydrogen, advancing knowledge on its production. The economic analysis will come in handy in making decisions on the viability of biohydrogen production from hotel food waste.

1.7 Scope and limitation of the study

Given that food waste has many definitions that are conflicting definitions, and that the food service sector has different establishments, it was important to set clear boundaries to avoid misunderstanding about the coverage of this study. This study utilized serving-stage foods which included plate wastes (leftovers) and display (buffet) wastes prepared for consumption but never consumed, ending up in waste bins. It is not just a humanitarian or social concern when food is wasted in urban areas like Nairobi; it is an environmental and energy concern too. When food is wasted, the energy it took to grow, harvest, transport, package, and cook it, is also wasted. Waste management becomes a challenge, contributing to the environmental degradability of cities. Since waste is sensitive to the geographical environment, it is important to state that the results of this study are for food waste from hotels in Nairobi City County, Kenya. Many studies have been undertaken on food waste but minimal research has been conducted on bio hydrogen generation from cooked food wastes by simulation and optimization.

There being many simulation and optimization software, the current study focused on Aspen Plus and Minitab's Response Surface methodology software respectively. The

economic viability of the process was analyzed using net present value, internal rate of return, payback period, discounted payback period, and profitability index.

1.8 Theoretical and Conceptual Framework

1.8.1 Theoretical Framework

This study was grounded in the principles of biomass gasification. The system leveraged food waste as a feedstock being characterized and converted into a synthesis gas (syngas) rich in hydrogen, carbon monoxide, carbon dioxide, methane and other gaseous components. The process integrated air gasification, gas cleaning and upgrading to produce high purity bio hydrogen through development of a simulation and optimization model based on characterized data. Optimization explored the optimal operational conditions for food waste gasification. This theoretical framework formed the foundation of the research on air gasification of food waste, providing a clear understanding of the principles, variables, and contexts that influence the process. It guided the experimental design and analysis of the gasification process, enabling the identification of optimal conditions for maximum biohydrogen yield. Figure 1-1 summarizes the framework of the study.

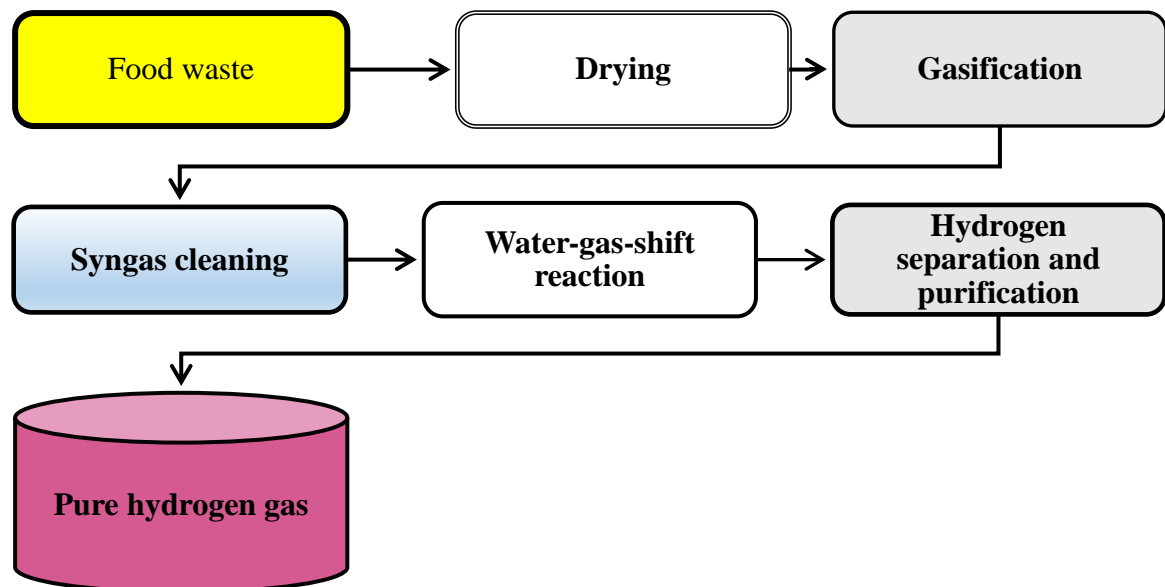


Figure 0-1: Schematic diagram of the Theoretical and Conceptual framework

1.8.2 The Conceptual Framework

The conceptual framework consisted of food waste collection from hotels, sorting, pre-treatment, and preparing them for characterization. The process was then modelled by simulation of a bio-hydrogen production system via air gasification, where food waste was converted into Syngas (H_2 , CO , CO_2 , and CH_4). The gas was further cleaned, purified, and stored for utilization. This framework provided a sustainable waste-to-energy solution for hotels in Nairobi, reducing waste disposal challenges while producing a clean energy carrier.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical background

Biohydrogen from biomass feedstocks is a renewable biofuel that can be produced biologically, biochemically, and thermochemically. Hydrogen is an environmentally friendly fuel that is clean since it produces water when combusted, unlike other fuels. The minimal use of hydrocarbons in energy generation makes it an optimistic fossil fuel alternative as it is a sustainable energy supply (Sazali, 2020). It only exists in compound forms and, hence can only be produced through a dissociating process from its compounds. Several methods of hydrogen production differ only in the energy used during the process (Ardabili et al., 2018). Other biofuels include biogas, bioethanol, biomethane, biodiesel, bio-oil, and biochar. All these are produced from biomass using various raw materials (feedstock), reactor types, production methods, and technologies.

2.1.1 Biomass classification

Biomass is always classified based on its origin, composition, possible conversion technologies, and properties (Ilham, 2022). Common classification properties include: Virgin biomass, derived from natural sources like forests, agriculture, and aquatic plants; Waste biomass that includes Municipal Solid Wastes, agricultural residues, and industrial waste (Kalak, 2023). Energy crops, such as sugarcane and switchgrass, can also be grown for energy production (G. Pathak & Dudhagi, 2021).

2.1.2 Biomass Conversion

This is the process of transforming organic matter (biomass) into energy carriers like heat, power, fuels, or chemicals. It involves various technologies that break down biomass components (carbohydrates, lignin, and lipids) into usable products (Barot, 2022; Jha et al., 2022; R. Wu, 2025). Examples of biomass conversion processes include:

- Converting wood into bioethanol (El Hage et al., 2023)
- Producing biodiesel from plant oils (De Paola et al., 2021)
- Generating electricity from agricultural produce (Rojas-Flores, 2022)
- Generating biohydrogen from food wastes (Kazmi et al., 2024)

The main goal is to efficiently valorize biomass resources into valuable energy products. Bio-hydrogen production from food wastes is grounded in two main conversion technologies, namely, biochemical and thermochemical as depicted by Figure 2-1.

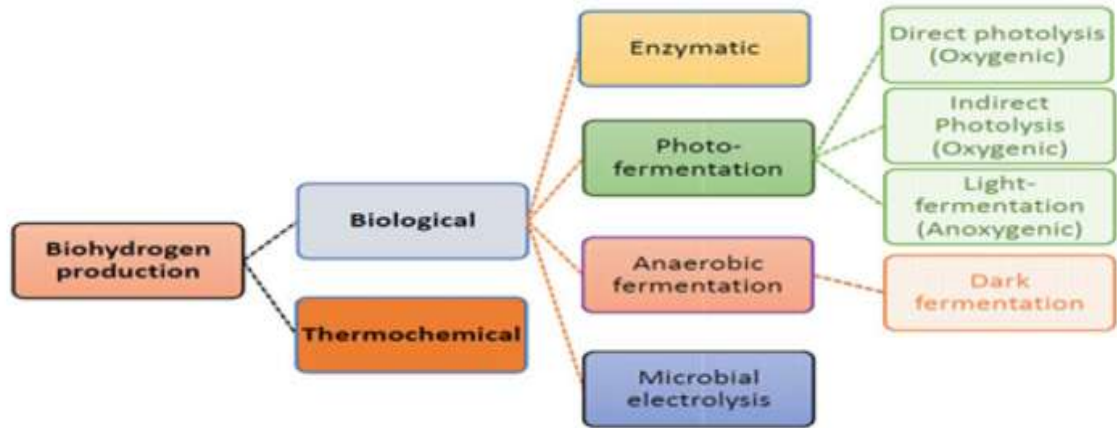


Figure 2-1: Illustration of different routes of bio-hydrogen production(Kuppam et al., 2017)

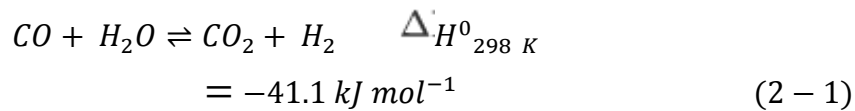
2.1.3 Biomass gasification

This is the thermochemical process that converts biomass into a synthetic gas (syngas) at high temperatures of 700 °C-1000 °C with controlled oxygen levels (Maitlo et al., 2022). The syngas typically contains H₂, CO, CO₂, CH₄, and other gases. It is applicable in power generation, chemical synthesis, and the production of biofuels such as methanol and biohydrogen. It has been observed that biomass gasification technologies keep improving for hydrogen production (Tezer et al., 2022)

Technological advancement has enabled hydrogen to be produced in high volumes through combustion, pyrolysis, gasification, and liquefaction. Studies show that Pyrolysis and gasification are economically viable approaches that can be explored for industrial production due to their competitiveness in future large-scale production (Kaur et al., 2019).

Methane's steam reforming, reaction of water gas shift, and application of pressure swing adsorption is an interesting pathway in the hydrogen generation from organic waste (Abd et al., 2023; Cruz et al., 2018). To get a robust simulation model, the use of validations was based on the previous studies by (Cruz et al., 2018; García et al., 2021;

Park et al., 2020; Phan et al., 2022). Minimizing Gibbs free energy or the Equilibrium constant is used to calculate thermodynamic equilibrium. The presence of solid carbon produced by reforming methane could hinder the approach of equilibrium constant hence the need to apply Gibbs free energy for this study. The main units of the biohydrogen generation system were intake points where food waste was dried before being decomposed and pyrolysis to generate syngas that was reformed at 550 °C reaction temperature (Park et al., 2020), system pressure below 32bar (Abd et al., 2023). The water-gas-shift reaction is a redox reaction expressed below (Chen & Chen, 2020)



The above reversible and exothermic reaction was triggered by the presence of carbon and water in the Water-Gas-Shift reactor, overcoming the energy barrier of the chemical reaction. Oxygen in water is converted to carbon monoxide in the reactor, allowing water to serve as the hydrogen source (Chen & Chen, 2020).

- **Common factors affecting biomass gasification**

Biomass gasification requires either steam, heat, air, or oxygen (Hedayati Moghaddam et al., 2023) to convert biomass into hydrogen via the production of synthetic gas. There are many variables and operational factors affecting bio-hydrogen generation via gasification due to its complex array of chemical reactions. These include substrate concentration, temperature, steam-to-biomass ratio, carbon-to-nitrogen ratio, air-to-fuel ratio, pressure, fuel feed rate, and equivalence ratio (Pathak et al., 2023)

- a) **Substrate (feedstock) composition**

Hydrogen production is entirely dependent on the biomass (feedstock) that is being fed into the gasifier. During the present-day development of biomass gasification for hydrogen generation, Song et al., (2022) found that biomass with high concentrations of fixed carbon, ash, volatile matter, and lignin is more suitable for hydrogen production. They also outlined that the particle size of biomass affects the mass and heat transfer conditions. The smaller the size of the particle the greater the area of contact between biomass and the gasifying agents. This enhances the chemical reactions rate increasing

the rate of gasification reactions. It is also revealed that increase in moisture content promote water gas shift reaction due to greater gas-phase product combustion during gasification process (Song et al., 2022).

b) Temperature

Literature reveals that higher temperatures favor hydrogen generation during the gasification process (Martins et al., 2023). It is simply because endothermic and Boudouard reactions that enhance hydrogen generation ascribe to elevated temperatures. This is well explained in the overview of increased gasification of biomass for hydrogen generation study by Rubinsin et al., (2024). Similar observations of hydrogen generation being favored by high temperatures are made in different studies (Rubinsin et al., 2024; Sarmah et al., 2023; Tang et al., 2024).

c) Steam to biomass ratio

This factor plays a crucial role in the steam gasification process, as its enhanced form favors water-gas-shift and steam reforming reactions, thereby improving hydrogen yields. Steam-to-biomass ratio has been investigated in several studies and its effect evaluated (Gani et al., 2023; Nunes, 2022; Z. Yu et al., 2024). In a study on biomass pretreatment for hydrogen-rich syngas production by Shen (2024), it was revealed that the steam-to-biomass ratio is crucial in achieving high yields of hydrogen during the gasification process. The exergy analysis and cold gas efficiency evaluation study by Tavakoli & Saidi (2024), revealed that enhanced steam-to-biomass ratio and temperatures improved the exergy efficiency throughout the alga biomass steam gasification process. Steam injection in the gasification process increases the molar flow rate of hydrogen due to water-gas-shift reactions, increasing the hydrogen yield (Safarian et al., 2022).

d) Air-to-fuel ratio (A/F)

The air-to-fuel ratio is the amount of air required to burn a specific fuel quantity in a stoichiometric combustion. At this point, the optimal amount of oxygen and fuel produces the highest heat possible, achieving extreme combustion efficiency. A well-maintained stoichiometric combustion process requires a proper air-to-fuel ratio since a

decreased A/F ratio deteriorates combustion efficiency, causing high smoke (Saranya et al., 2022). At the same time, an increased A/F ratio increases the reaction temperature, decreasing the process efficiency as more carbon dioxide is produced. It is a crucial parameter in hydrogen generation from biomass during gasification process since its high value decreases the heating power of syngas (González & Sandoval, 2020).

e) Equivalence ratio (ER)

Another important parameter in air gasification is the equivalence ratio as it directly influences efficiency. This is a correspondent air used in gasification to stoichiometric air (Liu et al., 2021). For a good gasification efficiency, an equivalence ratio must be maintained at 0.2-0.4 (Ramalingam et al., 2020). In an experiment to investigate air gasification of olive cake at low temperatures by Gálvez-Pérez et al., (2021), an equivalence ratio was maintained at 0.3 while 0.35 was maintained by El-Shafay et al., (2020) in their experimental and numerical study of sawdust gasification.

f) Gasifying agent

There are five main gasifying agents, namely; oxygen, air (O_2 , N_2), steam, hydrogen, and carbon dioxide in the gasification process. The main objective is to convert feedstock into biofuel (Ramalingam et al., 2020). Steam has attracted great interest as a gasifying agent since it is cheaper than oxygen in production. Comparing the gasifying agents, Xu et al. (2018) noted that the agents in steam gasification promote steam-char reaction and steam-methane reforming reaction, greatly increasing the hydrogen content. Since steam as a gasifying agent promotes hydrogen production, the literature reveals that the simplest, cheapest, and most explored gasifying agent is air (Kurian et al., 2022). Regardless of this, air as a gasifying agent produces the low caloric value of producer gas due to it being diluted by nitrogen. Oxygen is preferable if producer gas with high calorific value is to be obtained; nonetheless, oxygen as a gasifying agent is very expensive, increasing the complexity of the gasification process, hence unsuitable for commercial application. The summary of gasifying agents and their characteristics is analyzed by Bisht & Thakur (2019).

2.1.4 Characterization techniques

Biomass characterization is the analysis of physical, chemical and thermal properties of biomass materials, such as, agricultural residues, wood, municipal solid wastes including food wastes. Physical properties are the size, shape, density, and moisture content (Glass & Zelinka, 2021; Mauer, 2024); The chemical composition are the cellulose, hemicellulose, lignin, and ash content of biomass (Wu et al., 2025) while elemental analysis involves determination of carbon, hydrogen, oxygen, nitrogen and Sulphur in feedstock (Iurchenkova et al., 2024; Taqvi et al., 2024). The calorific value and decomposition behavior of biomass can also be established during characterization. Basically, characterization techniques in bioenergy generation are; proximate, ultimate, compositional, and thermal analysis respectively. The molecular structure of biomass can be obtained by Spectroscopy (Ahmed et al., 2024), while energy content (high and low heating values) by Calorimetry (Adeleke et al., 2024).

2.1.5 Modelling

Modelling is the process of using mathematical and computational tools (software) to simulate and predict the behavior of bioenergy systems. Depending on the kind of study, software like Minitab and Aspen Plus are used during this process. For instance, response surface methodology and artificial neural network were used to model bioenergy production from biochar-improved anaerobic digestion (Zhan & Zhu, 2024). A high breed multi-criteria decision-making approach was applied to analyze waste wastewater micro algae culture system for bioenergy production (Liu et al., 2024). Kumar et al. (2024) modelled hydrogen production from the steam reforming of methane and biogas using the COMSOL Multiphysics 5.6 software. A novel optimization approach can also be applied for biohydrogen production using alga biomass (Sharma et al., 2024). Modelling helps optimize design, operation and scale-up of bioenergy systems.

2.1.5.1 Simulation

Simulation is using models to mimic real-world systems. The key aspects of simulation include system representation, where real-world processes are translated into mathematical equations. Numerical methods are applied in simulation to solve

computational equations to predict the behavior, while validation is comparing simulation outputs with real-world data for accuracy.

Since gasification is a complex process, modeling is advisable to appreciate and interpret its characteristics and study several parameters' effects on its performance. This is achieved by commercially available computer-based simulation and modeling software like Aspen Plus (Ranjan et al., 2023), Aspen Hysys (Kartal et al., 2022), Fluent (Rao & Barman, 2023) , and Chemkin (Li, et al., 2022) . Model formulation may include identifying the appropriate procedure for bio-hydrogen production. Schematic diagrams may be used to visualize the biohydrogen production process. For instance, Babatabar & Saidi (2021) developed a simulation process using Figure 2-2 to guide the steps that would be applied in their process simulation and optimization study.

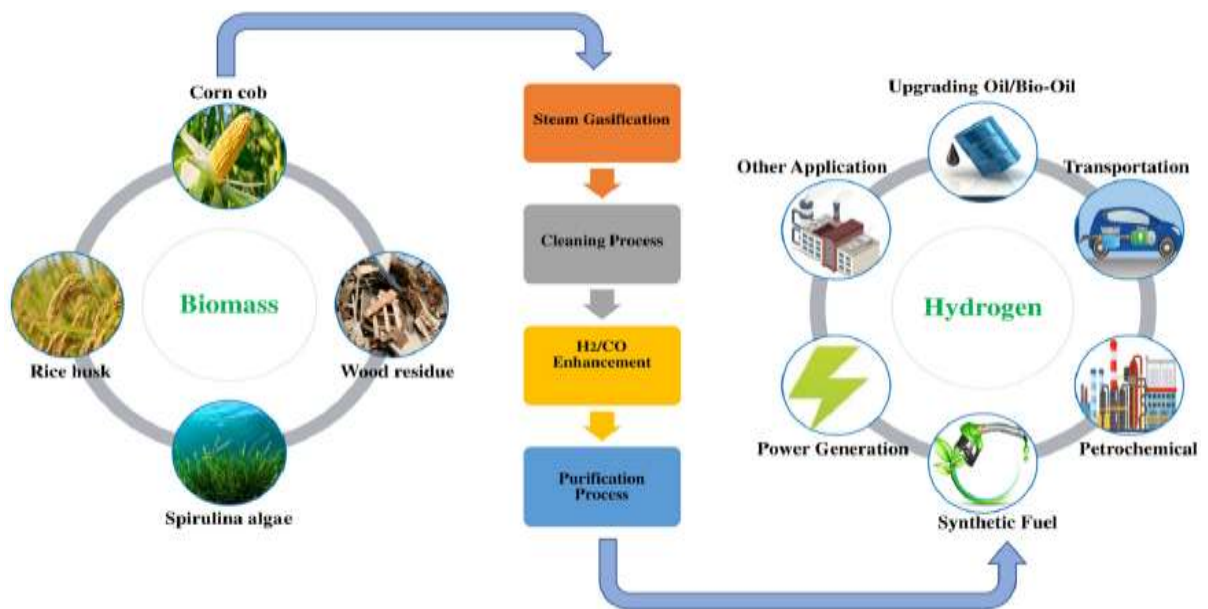


Figure 2-2: Schematic step for biohydrogen production (Babatabar & Saidi, 2021)

Process simulation models may vary from situation to situation, but generally, one has to follow the steps in Figure 2-3.

1. Problem definition > 2. Model formulation > 3. Data identification and collection > 4. Model testing/implementation/Simulation > 5. Model verification and validation > 6. Model experimentation /Scenario testing > 7. Model Analysis and interpretation > 8. Documentation (Mohammadidoust & Omidvar, 2020).

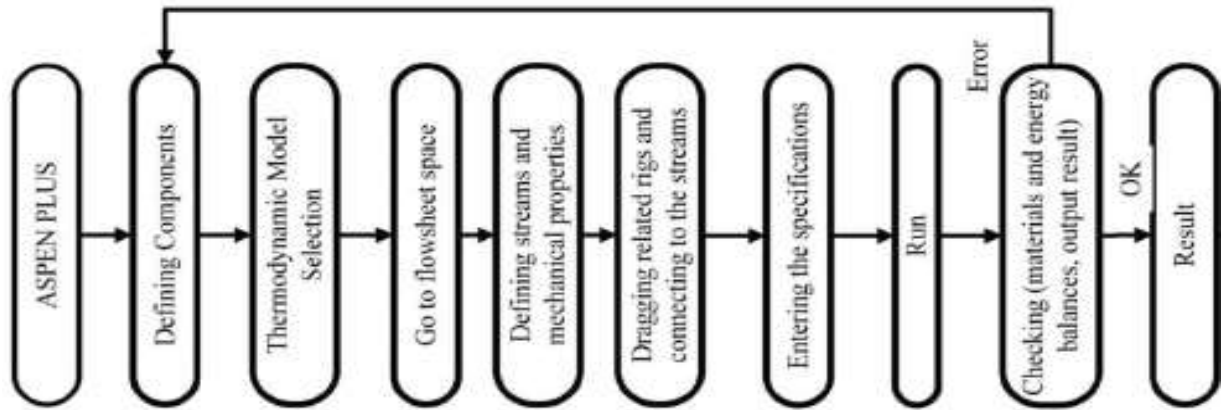


Figure 2-3: Aspen Plus flow process simulation (Mohammadidoust & Omidvar, 2020)

The yield may be calculated using the Equation 2-2

$$Yield = (1 - \text{water fraction in food waste}) \times \text{Fraction of component in food waste}$$

(2 – 2)

2.1.5.2 Optimization

Optimization is the best way of finding the best solution among alternatives, often using mathematical techniques. The key aspects here are the objective function defining what to optimize, their constraints, i.e., limits on variables, and using algorithms to search for optimal solutions. For instance, bio-hydrogen generation from food waste is a complex process involving fermentation or gasification that is influenced by various factors (Elgazar et al., 2024; J. Wang & Yin, 2019). To understand the relative interaction among the factors, and increase the reaction rate and yield, optimization statistical methods are used to screen the best combination of the factors that can give maximum yield.

The experimental design methods applied in screening and analyzing the effect of factors are Taguchi, Plackett-Burman, full/fractional factorial, single or multi-factor-at-a-time, Box-Behnken, and central composite designs, neural network ANN, and steepest inclined or declined, and genetic algorithms are applied. Response surface methodology is frequently used in optimization (Bouchareb et al., 2021; Thomareis & Dimitreli, 2022; Z. Xu et al., 2022).

- **Optimization principles**

For any optimization to take place, some principles must be followed using Figure 2-4. In an experimental design, selected factors are controllably varied for their effects to be obtained on a specific response for result analysis. This design can be grouped into two categories depending on the number of factors being investigated: Single or multiple-factor design. It is advisable to understand the effects of these factors on the yield theoretically and experimentally. Whether through fermentation or gasification, the hydrogen production process complexity requires an experimental design to analyze the outcome of these factors in the process. For better understanding, optimization can be used to improve its production performance (Wang & Yin, 2017).

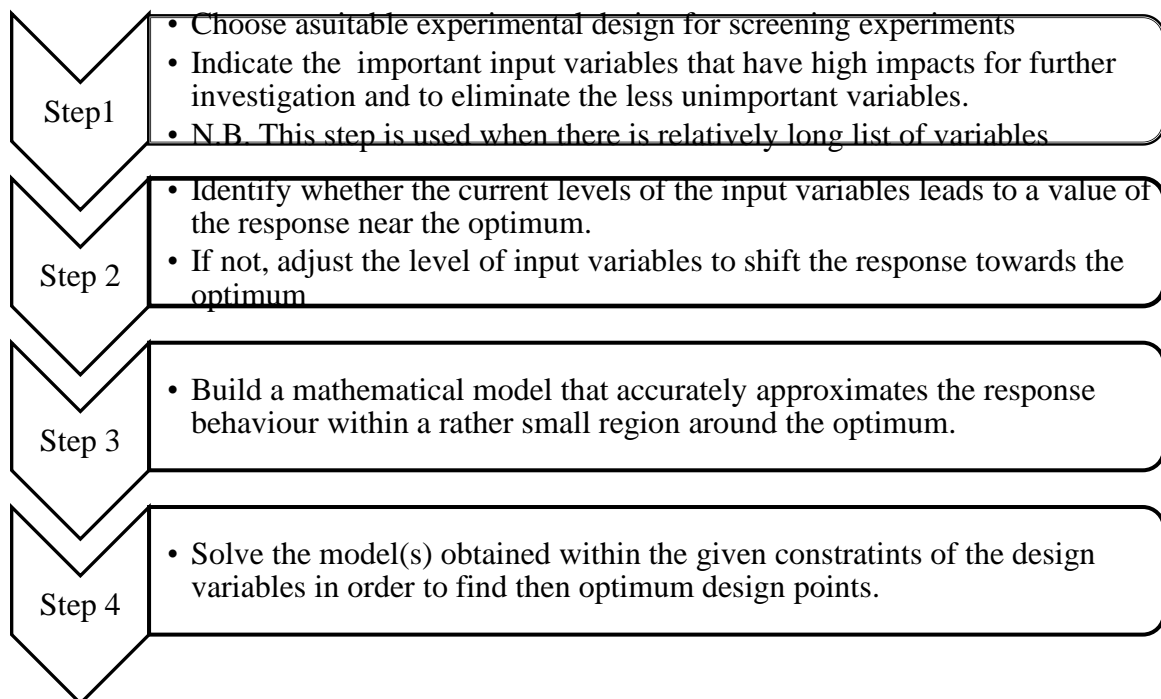


Figure 2-4: Sequential steps in optimization process using RSM (de Oliveira Filho et al., 2018)

Researchers are studying optimization using different parameters. For instance, Alavi-Borazjani et al., (2021) optimized the process of dark fermentation by the Taguchi Method, enhancing the biohydrogen production from municipal solid waste. From the figure below, it was observed that there was a quantitative increase in biohydrogen after optimization. Ramzan et al., (2011) designed a simulation model for the gasification of municipal solid, food and poultry waste. Their three-stage model was used as a predictive instrument for optimizing the performance of the gasifier. They studied the

impact of temperature on synthetic gas composition and found that higher temperatures increased the production of H₂ and CO. They modeled and analyzed food waste gasification process for hydrogen production, whereby the effect of gasification temperature and the hydrogen production capacity of the region was studied. The study acknowledged that increased temperature enhances hydrogen production, while regional capacity had no influence. Kitchen waste gasification in an updraft fluidized bed gasifier was simulated by Fatema et al., (2022). They observed that 67% of kitchen waste was converted into gases at the highest temperature of 800 °C while moisture content did not affect the process significantly. Mehdi et al., (2023) performed a steam gasification model for syngas generation using solid wastes from the municipal. They found out that an increase in temperature from 700 °C to 1300 °C favored hydrogen concentration, which improved from 37 to 51 mol%.

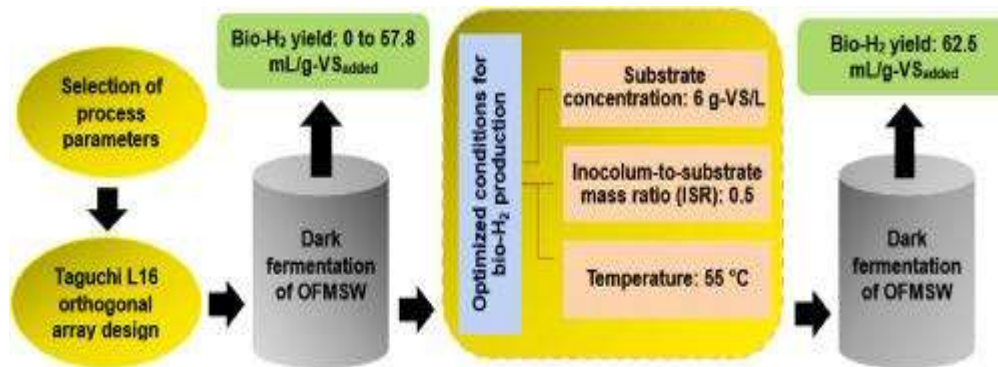


Figure 2-5: Example of an optimized system using three factors (Alavi-Borazjani et al., 2021)

- **Minitab and Response Surface Methodology (RSM) as optimization tools**

Minitab software can generate run-based designs for up to 47 factors and 12 to 48 runs. It is noted that the number of factors must be less than the runs thus a 15-run design can only allow one to estimate the effects of up to 14 factors. The full, fractional and general factorial designs can be utilized to come up with the full experimental design. Plackett-Burman and Box Behnken designs are also applied, especially when many parameters are to be studied. Experiment can be performed and response data collected and fit using a binomial model before analyzing it to evaluate the effective factors on the response. Optimization can then be conducted for each response (El-Azazy et al., 2019; Razon et al., 2019; P. Yu et al., 2018).

Evaluation of bio-hydrogen production is continuously being studied using different feed stocks. Waste water from a cassava processing plant and two microbial consortia from different environments in Brazil were studied by Martinez-Burgos et al., (2020). A Box-Behnken design optimized the production, maximizing the yields with hydrolyzed substrate. The kinetic parameters k , q , and u were highly observed in both consortia. Microbial families' relative abundance as fermentation progresses at an interval of 16 and 24 hours, generating 90% of biohydrogen.

- **Optimization of bio-hydrogen production by RSM**

Two main designs in Response Surface Methodology could be applied to scale up bio-hydrogen production.

- a) **Central composite Design (CCD)**

This is a factorial response surface design with 2k additional points called star or axial points, allowing quality of the prediction to be the same in any direction. If $\alpha=1$, the design is face-centered with only three factors (-1, 0, +1) used.

- b) **Box-Hagen Design**

This is an embedded, quadratic and fractional design that require few runs than normal factorial techniques to generate maximum responses. Three levels of each factor are required to maintain the higher surface definition. Factors (independent variables) affecting the process are identified first, then their effects are analysed on the response (dependent variable).

Comparing with the central composite designs, Box-Hagen Design is inferior on orthogonality. Whether using CCD or Box-Hagen Designs, one needs to run an experiment first to get response, then input values back into Minitab.

- c) **Definition of custom response surface design**

A custom response surface design in Minitab is applied when either CCD or Box-Hagen cannot be applied due to numerous number of runs. Studies have been done to optimize bio hydrogen from different feed stocks. Liu et al., (2018) optimized generation of bio-hydrogen and acids that are volatile from food waste using Response Surface

Methodology (RSM); Ulhiza et al., (2018) optimized bio hydrogen generation from sago waste water while Yadav et al., (2021) optimized simultaneous enhancement of bio hydrogen and bio butanol production. Nazarpour et al., (2022) designed and fabricated a micro-photo bioreactor to produce the bio-hydrogen using RSM to optimize variables affecting the production. A quadratic model predicted the behaviour of samples in 20 treatments and 6 replications using Central Composite Design. Sulphur concentration (0.5–1%) was used as an independent variables for evaluation, (5–120 h) running time and biomass concentration of algal (50–100 g/L). Optimal conditions for bio hydrogen generation in this experiment were identified as 0.75% sulphur concentration, 101.96 hours run time and 53.31g/l biomass concentration producing 66.32mL g-VS-1 bio-hydrogen. Conclusively, there was prediction of bio hydrogen extraction and generation in photo bio reactors using response surface methodology.

2.1.6 Project Economic Analysis

The aim of every project economic analysis is to efficiently allocate scarce resource to ensure citizens have benefited and their welfare raised. Therefore, Project Economic Analysis (PEA) provides direction, support and focus through economic competitiveness, resulting in clear direction towards cost reduction of similar projects. Life-cycle and measurement commercialization is done during this analysis (Gebremariam & Marchetti, 2018). Project Economic Analysis can be conducted through cost-benefit analysis, cost minimization, and cost-effectiveness analysis. Maximizing resources for optimum benefits is realized when these analyses are done.

2.2 Summary of related studies

Singh & Tirkey, (2022) modeled and thermodynamically performed optimization of air gasification of poultry litter pellets for Hydrogen production based on Gibbs free energy. They obtained an optimum temperature of 830.30 °C, an equivalence ratio of 0.2, and a moisture content of 16.36%. Kombe et al., (2022) modeled and evaluated the maximum operating conditions of an air gasification process for syngas generation from rice husks using Aspen Plus and RSM. They found out that high temperatures favored CO and H₂ production as well as the H₂ yield. In the process modeling and optimization of biomass steam gasification using RSM study by Zaman et al., (2020), the optimum temperature was from 750 °C to 900 °C and steam to biomass ratio of 0.70 to 0.81. Inasmuch as RSM is a popular method of optimization (Uslu, 2020), very few air gasification process

optimization studies for hydrogen production using food wastes from the hotel industry are reported. Faraji & Saidi, (2022) optimized hydrogen-enriched syngas production from the biomass air gasification process of ground nut shell using RSM. Shi et al., (2023) optimized hydrogen generation from sewage sludge and poultry litter waste gasification using RSM. An experimental study for hydrogen generation from hydrothermal co-gasification of sorghum and □an lignite biomass was optimized by Seęer et al., (2020) using RSM with a Box-Behnken design (BBD). Lestari et al., (2024) used RSM to optimize a process variable of hydrogen generation from *paraserianthes falcataria*, a saw dust mill. A promoted calcium hydroxide absorption was used in the gasification process.

For any project accomplishment, a comprehensive economic analysis is required to inform its viability. It evaluates project scenarios, topics, and actions to understand its profitability and losses. The advantages and disadvantages are investigated to enhance the decision-making process. Case in point, a thermodynamic and tech-economic analysis of hydrogen generation from food waste was studied by Zhao et al., (2024) through torrefaction integration with steam gasification. The authors simulated a hydrogen generation process by integrating torrefaction and steam gasification. Their focus was on steam and direct gasification taking into consideration the techno-economic, thermodynamics, and sensitivity analysis. The techno-economic analysis outcome implied that steam gasification had a shorter payback period, larger internal rate of return, and higher net present value displaying a higher commercial potential than direct gasification. Another economic analysis and optimization study by Inayat et al., (2017) involved biohydrogen generation from oil palm waste via steam gasification, which revealed a low production cost for hydrogen generation. Response Surface Methodology optimized variables affecting biohydrogen generation from microalgae in Nazarpour et al., (2022) study. A micro-photo reactor was designed and fabricated as a quadratic model predicted sample behavior. Twenty runs and six duplications in the central point were applied using a Central Composite Design. Algal biomass concentration, sulfur concentration, and run-time were evaluated as independent variables. Substrate concentration and content of sulfur had very little effect, while test length had a significant impact. Predicted values under optimal conditions and experimental values of response variables were similar, concluding that the Response

Surface Methodology can predict the extraction and generation of biohydrogen in photobioreactors. A technological advancement and economic analysis for sustainable hydrogen generation was also done by Ahmed et al. (2022), advising upcoming research to concentrate on lowering the cost of renewable hydrogen generation. Summary of other related studies is highlighted in Table 2-1.

Table 2-1: Summary of other related studies

Feedstock	Factors studied	Model/process	Bio hydrogen yield	Reference
Lignocellulosic biomass processing (Xylose)	Fermentation or digestion time, pretreatment, relative pressure of biogas, volatile fatty acids	Structural (casual) modelling + benefit analysis + genetic algorithm = Hybrid optimization Technique	High yielding	(Mahmoodi-Eshkaftaki & Mockaitis, 2022)
Gathered online data	Feedback control strategy	Modified Gompertz	Optimum production	(Jiménez-Ocampo et al., 2021)
Cattle manure and food waste (co-digestion)	substrate concentration, culture mixing ratio and hydraulic residency time (HRT)	Box–Behnken design/ mesophilic partial -continuous process	Maximized hydrogen generation	(S. Liu et al., 2020)
Organic municipal solid waste	inoculum-to-substrate ratio (ISR), Substrate concentration and temperature	Taguchi method L16 orthogonal array design	The measured yield matched predicted yields	(Alavi-Borazjani et al., 2021)
Cornstalk by (<i>Clostridium butyricum</i>)	Inoculation quantity, Temperature, pH and concentration of the substrate	Response Surface Methodology	Maximum hydrogen yield	(Lu et al., 2019)
Potato Waste, Anaerobic Mixed Sludge	pH, temperature, Potato waste concentration, and fermentation time.	Response surface methodology (RSM)	large-scale production	(Sekoai et al., 2019)
activated sludge and date syrup	Temperature, pH, waste date syrup concentration and fermentation time,	2 ^k factorial design and RSM	High hydrogen production	(Kamyab et al., 2019)

2.3 Identified research gap

Although literature highlights several hydrogen generation from biomass gasification simulation studies using Aspen plus integrated with RSM, many of them focused on the essential simulation and optimization procedures for hydrogen-rich syngas production. This study has established that little has been done on syngas purification together with RSM optimization and economic analysis of hydrogen production. In addition, the literature evaluation on RSM implies that little has been done to optimize the air gasification of food waste from the hotel industry using RSM. Moreover, an RSM design matrix was constructed using 352 runs of simulated results of Aspen Plus. The hydrogen production yield was subjected to a five-tool economic analysis contributing to the significance of the present study. Therefore, this study characterized food wastes, simulated, optimized, and carried out a comprehensive economic analysis using NPV, IRR, PI, PBP, and DPBP tools for the viability prediction of hydrogen production by air gasification of food waste.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Nairobi City County (Figure 3-1), one of Kenya's 47 counties. Nairobi is a multicultural and cosmopolitan city (Karoki et al., 2018), with a population of 4,397,073 residents, a population density of 6,247 people per square kilometer, and an annual growth rate of 4.1% as of the 2019 census. Kiambu County borders Nairobi City County to the North West, Machakos County to the East, South, and Kajiado County to the South, South West with the Ngong Hills to the west (Lusimbo, 2019; Mathews, 2019). The Central Business District (CBD) is the city's vibrant economic core, featuring a dense concentration of high-rise buildings like Times Tower, financial institutions like the Central Bank of Kenya, and government offices in Nyayo House, bordered by Uhuru Highway to the west, Haile Selassie Avenue to the south, and Moi Avenue to the east. Other key features include iconic buildings like the Kenyatta International Conference Centre (KICC), the Nairobi National Museum, and a mix of modern skyscrapers alongside historic colonial-era structures.



Figure 3-1: Nairobi County location from Map data 2025

3.2 Determination of the physical and biochemical characteristics

In any energy conversion technology, it is very critical to assess the potential of the feedstock that would be used as a substrate. It is noted that not all biomass materials can be used as feedstock for biohydrogen production. Inasmuch as biomass blending could provide a steady flow of substrate, the potential of its supply and its variation in quality and composition could affect the processing, operations, performance, efficiency, and optimization of the bioenergy production system (Edmunds et al., 2018). Therefore, a comprehensive food waste characterization was crucial in this study, as it could inform which level the food waste lies in the grading system that evaluates biomass potential.

3.2.1 Collection and Preparation of Substrate for Characterization

Food wastes were collected from restaurants, cafes, canteens, and catering services within Nairobi City County. A 20 kg mixture representing the common food waste ingredients was prepared. The mixture was subdivided into 5 samples of 4 kg each, where physical sorting to remove non-food wastes was done. Scooping of food waste into random containers resulted in the following mixture.

Sample 1: Rice, cabbage, macaroni, watermelon, and chicken

Sample 2: Rice, beans, Potato wedges, kale, beef, and pineapple

Sample 3: Spaghetti, Carrots, eggplants, fish, spinach, and eggs

Sample 4: Maize, pigeon peas, rice, beef, carrot, and sweet potatoes

Sample 5: Matoke, Beef, cabbage, cowpeas, and Spinach.

The proximate and ultimate analysis determinations were guided by the Association of Official Analytical Chemists (A.O.A.C) International Standard Methods. Crucibles, desiccators, muffle furnace (Model: Wise Therm), blender/grinder (Model: EFBG-1551), Magnetic stirrer (MS-Pro 85-1), Analytical balance (Model: WANT FA2204G) and Laboratory oven (DHG-9025) were applied in this study (Fatema et al., 2022; Mehdi et al., 2023). Total Kjeldahl Nitrogen (TKN) using Kjeldahl Protein Apparatus (Serial number: TP2017330715) was used for nitrogen analysis (Mrosso et al., 2023). U-V spectrophotometer (Model no: BK-UV1200) was used for the analysis of sulfur (Passos

& Saraiva, 2019). In the simulation process, hydrogen data was obtained using equation 3-1 predicted by Nhuchhen (2016) and Oxygen was calculated by difference.

$$H = 55.3678 - 0.4830VM - 0.5319FC - 0.5600A \quad (3-1)$$

Where: H- Hydrogen, VM- Volatile Matter, FC- Fixed Carbon, and A - Ash.

For accuracy purposes, the biochemical composition of the food waste was determined in triplicate unless stated otherwise.

3.2.2 Analysis

3.2.2.1 Analysis of acidity/alkalinity of samples by pH Measurement

5 g wet samples were added to a 50 mL beaker containing distilled water to be used as a sample solution for pH measurement. For accurate pH measurements, a three-point calibration of the pH meter (pH 4, 7, and 10) was performed. Electrodes were then placed in the sample solution. Measuring probes of a pH meter were lowered into a beaker, and the function selector was turned from the standby position to the pH position. Readings were recorded for each sample, and the meter was turned off. A portable, locally available pH Meter for Food and Dairy Products was used for this study.

3.2.2.2 Proximate Analysis

The determination of the Moisture Content (MC), Total Solid (TS), Volatile Solid (VS), and Ash content was performed as per the Association of Official Analytical Chemists (A.O.A.C.) International Standard Methods. Post-consumer food waste samples were weighed while wet, then placed in the air-dry oven set at a temperature of 60 °C and left for two days. The air-dried samples were then re-weighed. The weight change was calculated as a percentage of moisture at 60 °C. This was critical as food samples were to be analyzed on a dry basis. Therefore, samples were further subjected to oven drying at 105 °C to determine the Total Solids. The difference in weight before and after oven drying was used to establish moisture contents according to Okos et al., (2018). The Total Solid content was calculated thereafter by subtracting the percentage moisture content from 100%. The samples were then placed into a muffle furnace, set at the temperature of 550 °C for 24 hours to get the Ash that would facilitate Volatile Solid calculations.

$$\% \text{ Moisture Content (MC)} = \frac{\text{Dry weight at } 60^{\circ}\text{C} - \text{Dry weight at } 105^{\circ}\text{C}}{\text{Dry weight at } 60^{\circ}\text{C}} \times 100 \quad (3-2)$$

$$\% \text{ Total Solid (TS) or Dry Matter} = 100 - \text{MC}\% \quad (3-3)$$

$$\text{Ash weight (g)} = \text{TS weight (g) at } 550^{\circ}\text{C for 24 hours in a muffle furnace} \quad (3-4)$$

$$\% \text{ Volatile Solids (VS)} = \frac{\text{Total Solid weight (g)} - \text{Ash weight (g)}}{\text{Total Solid weight (g)}} \times 100 \quad (3-5)$$

Fixed Carbon- This is the ignitable solid residue that remains when an organic matter is subjected to 750 °C temperature for more than 7 minutes. Fixed carbon was calculated using equation 3-6 (Kamran, 2021; Rago et al., 2018)

$$\% \text{ Fixed Carbon (wet basis)} = 100 - \% \text{ MC} - \% \text{ VS} - \% \text{ Ash} \quad (3-6)$$

3.2.2.3 Lipid determination

The Soxhlet Extraction Method was used in determining the lipid content in the feedstock. In this method, 1 g of food sample was put down in a well-prepared thimble-like filter paper, loaded into the Soxhlet extractor chamber with a condenser, and placed onto the flask containing 300 mL of methanol solvent. The apparatus with the base of the flask was placed onto the heating mantle. Methanol solvent was heated, the vapor moving to the distillation arm and flooding into the chamber housing the thimble. The methanol vapor traveled through the condenser dripping back slowly filling it with warm solvent and dissolving some desired compounds. The chamber was automatically emptied by a siphon arm when almost full allowing the solvent to run back to the distillation flask. This process repeated itself for approximately 2 hours until the extraction was complete. A 250 mL 24 40 glass Soxhlet Extractor 40 38 Graham Coil condenser, one reservoir flask with a 250 mL, 180 W, AC220V/50P, Model No. ZDHW UMS-UK heating mantle was used. The percentage lipids was then determined using equation 3-7 (Boni et al., 2018; Cascant et al., 2017)

$$\% \text{ Lipid} = \frac{\text{weight of flask with extracted lipid (g)} - \text{weight of empty flask (g)}}{\text{Sample weight (g)}} \times 100\% \quad (3-7)$$

3.2.2.4 Nitrogen determination

Digestion

The Total Kjeldahl Nitrogen (TKN) method was used in determining the nitrogen content in the feedstock. 0.3 g of food waste sample was prepared in triplicate and a digestion mixture added. The mixture included 0.2 g selenium, 420 mL sulfuric acid, 4 g lithium sulphate and 350 mL hydrogen peroxide. The digestate was heated for the first 1 hour at 110 °C, followed by another 1 hour at 330 °C then finally at 350 °C until a pale yellow color was observed. The concentrated sulfuric acid formed ammonium sulphate.

Distillation

10 mL of the digestate sample was put in a test tube, adding 10 mL of 46% sodium hydroxide (NaOH) to the digestate. 20 mL of boric acid was put in a conical flask to collect ammonia gas in the cooled sample. The sample was distilled until it turned color to dark green.

Titration

0.05 M Concentrated sulphuric acid was used as a titrant. The amount of Nitrogen in the distillate was estimated based on the volume of the titre. For instance, the titre of 1.7 mL and 1.5 mL of titre were obtained for this estimation (Jamal et al., 2020; P. Singh et al., 2020)

$$\text{Nitrogen (\%)} = \frac{14 \times (\text{Titre-blank}) \times 50\text{mL} \times Q \times \text{H}_2\text{SO}_4 \times 100}{1000 \times 10\text{mL} \times \text{Sample weight}} \quad (3-8)$$

Where:

Q is the 0.05 M Sulphuric acid Concentration (ideal for acid-base titration);

14 g of Nitrogen is equivalent to 1 mole of Ammonia (NH₃);

50 mL is the total Volume at the end of the analysis procedure.

10 mL is the aliquot (portion) of the H₂SO₄ solution taken.

The percentage of Nitrogen was multiplied by a conversion factor of 6.25 to obtain the protein content according to equation 3-9 (Jamal et al., 2020)

$$\% \text{ Protein} = \% \text{ Nitrogen} \times 6.25$$

(3-9)

3.2.2.5 Potassium, Sodium, calcium, Lithium, and Barium determination

Potassium, Sodium, Calcium, Lithium, and Barium were determined using the flame photometry method. Flame emission spectroscopy (flame photometry) is centred on the intensity of emitted light that is measured when a metal is subjected to a flame. The color's wavelength informs on the element present and flame color highlights element concentration in a sample. This method is applied in easily excited elements in the first two columns on the periodic table as it is coupled with a high sensitive and reliable device that is simply read out.

- **Standard Potassium Solution**

10 ppm of potassium standard solution was prepared by measuring 100 mL stock standard solution and 5 mL of concentrated hydrochloric acid into a volumetric flask. The solution was filled up to 1 L. The standard solution aliquots were diluted with 0.5 % hydrochloric acid to produce 0.25, 1.0, 2.5, and 5 ppm of potassium. Triplicate solutions were subjected to a flame photometer for atomization with the wavelength set at 766 nm and 100% transmittance. Each concentration's emitted optical density was recorded, and a standard chart was drawn. From the developed standard chart equation, $y = 18.45x + 9.432$, with a regression $R^2 = 0.9937$, x was calculated as the potassium concentration in parts per million (ppm) when emitted optical densities (y) were known.

- **Potassium determination in Samples.**

1 g of food samples was digested in triplicate in 100 mL conical flasks. 10 mL of nitric acid was added, and conical flasks were put on the hot plate for 5-10 minutes. 5 mL of hydrochloric acid was added, and the solution was left to cool for 20 minutes. The content was shaken for approximately 5 minutes, and the solution was filtered.

With 1x4 dilution, 10 mL of each sample solution was taken and the volume made to 100 mL volumetric flask. 10 mL of this solution was made up to 500 mL in a volumetric flask. The diluted solutions were subjected to a flame photometer with the same wavelength of 766 nm, and admittance was still set at 100%. Triplicate sample readings with 1x4 dilution were recorded, and a standard chart was drawn. The concentration of potassium was then calculated using equation 3-10.

$$\text{Potassium (mg/100g)} = \frac{\text{Standard curve ppm} \times \text{Made up volume} \times \text{dilutions} \times 100}{\text{mass of sample (g)} \times 1000} \quad (3-10)$$

- **Standard sodium solution**

Preparation of a standard solution of 10 ppm of sodium was done by measuring 100 mL stock standard solution and 5 mL of concentrated hydrochloric acid into a volumetric flask. The solution was filled up to 1 litre. The standard solution aliquots were diluted with 0.5 % hydrochloric acid to produce 0.25, 1.0, 2.5, 5.0 and 10.0 ppm of sodium. Triplicate Solutions were subjected to a flame photometer for atomization with the wavelength set at 589 nm and 100% transmittance. Each concentrations' emitted optical density was recorded and a standard chart drawn. From the standard curve equation, $y = 6.7371x + 32.985$, with $R^2 = 0.9989$, x was calculated as the concentration in ppm when emitted optical densities (y) were known.

- **Sodium determination in samples**

With a 1x2 dilution, 10 mL of each sample solution was taken, and the volume was made to 100 mL volumetric flask. 10 mL of this solution was made up to 200 mL in a volumetric flask. Diluted solutions were subjected to a flame photometer with the same wavelength of 568 nm and transmittance was still set at 100%. The concentration of sodium was then calculated using equation 3-11

$$\text{Sodium (mg/100g)} = \frac{\text{Standard curve ppm} \times \text{Made up volume} \times \text{dilutions} \times 100}{\text{mass of sample (g)} \times 1000} \quad (3-11)$$

The above procedure was repeated for ***lithium, calcium, and barium*** with the wavelengths set at 670 nm, 622 nm, and 554 nm respectively.

3.2.2.6 Total Organic Carbon (TOC) determination

The standard procedure developed by Glosolan, (2019) was applied for the determination of organic Carbon using the Colorimetric method. The sample was prepared by measuring 1 g of dried powdered food waste and put in the digester tubes. 50 mL of 10% 0.34M potassium dichromate ($K_2Cr_2O_7$) was dissolved in 500 mL deionized water. 2 mL of potassium dichromate and 5 mL of concentrated sulfuric acid (H_2SO_4) were added into the digester tube and left to cool for 30 minutes. 20 mL of

distilled water was added to the mixture, shaken to mix well, and left overnight for U-V spectrometer analysis. 4 mg Sucrose standard was prepared by weighing 0.95 g dried at 105 °C for 2 hours and dissolved in 100 mL distilled water. The standard chart was recorded by the spectrophotometer. Total Organic Carbon (TOC) was calculated using equation (3-12).

$$\% \text{ TOC} = \frac{\text{Sample concentration} - \text{Blank sample} \times f \times mcf \times 100}{\text{mass of sample (g)} \times 1000} \quad (3-12)$$

Where f - correction factor and mcf - moisture correction factor (Kim et al., 2023)

3.2.2.7 Phosphorus determination

The U-V Spectrophotometric method was used for determination of phosphorus in the samples. With the spectrophotometer set at 830 nm, the concentration of the complex was measured. As the phosphorus concentration increased, the intensity of colour blue also increased. This conformed with Beer-Lambert equation which states that the absorbance is directly proportional to the concentration of phosphate in a sample (Mandru et al., 2023).

12.5 g of AR sodium molybdate was dissolved in 5M sulphuric acid and diluted to 500 mL with the 5M sulphuric acid. 1.5 g of AR hydrazinium sulphate was dissolved in distilled water and diluted to 1000 mL. 0.2197 g of AR potassium dihydrogen phosphate was dissolved in distilled water and diluted to 1000 mL.

25 mL of 50 ppm phosphorus was transferred into a 50 mL volumetric flask. 5 mL of the molybdate solution was added, followed by 2 mL of the hydrazinium sulphate solution, diluted to the mark, and mixed well. The flask was immersed in a boiling water bath for 10 minutes, removed, and put in a bucket full of ice for rapid cooling. After 5 minutes, the flask was shaken well, from which the sample was taken for absorbance measurement at 830 nm. This procedure was repeated using 30, 25, 20, 15, 10, 5, 1, and 0 ppm of the phosphorus standard solution and 10 mL of the unknown sample solution. A calibration curve using the standard phosphate solution was constructed, and the concentration of phosphorus in the unknown food sample was computed. From the generated standard curve equation, $y = 0.0399x$, with $R^2 = 0.986$, x was calculated as the concentration in milligrams per litre when absorbance (y) was known.

$$\% \text{ Phosphorus} = \frac{(\text{Phosphorus Conc.in sample} - \text{Blank}) \text{digested volume} \times 100}{\text{mass of sample (g)} \times 1000} \quad (3-13)$$

3.2.2.8 Sulphur determination

Sulphur in samples was determined using the U-V Spectrophotometric method as described below.

240 g of sodium chloride was dissolved in about 20 mL of distilled water. 20 mL of hydrochloric acid was added to the solution and diluted with distilled water up to 1 l volume to make a NaCl-HCl solution. 50 mL glycerol was added in 100 mL ethanol to form glycerol-ethanol solution. 0.15 g of anhydrous sodium sulphate was added to distilled water up to 1 liter volume to make the sulphate standard solution.

5 g of the powdered food was added to 50 mL of distilled water to make a uniform suspension which was filtered with filter paper. 50 mL of filtrate was added to 0.15 g of barium chloride, 10 mL of Glycerol-ethanol solution, and 10 mL NaCl-HCl solution. A magnetic stirrer was used for approximately one hour to mix the sample properly. The sample absorbance was measured using a spectrophotometer at a maximum wavelength of 420 nm and a blank solution of distilled water. Standard sulphate solutions of different strengths were used to draw a calibration curve as the absorbance for each was recorded (Nair et al., 2020). Sulphates formed from samples in mg/kg were 23.6, 18.6, 27.4, 36.3, and 23.4, respectively. Percentage Sulphur in samples was calculated using equation 3-14 according to Mandrile et al., (2020).

$$\% \text{ Sulphur} = \frac{\text{Weight of sulphate (s04) formed} \times 32 \times 100}{\text{mass of sample (g)} \times 96 \times 1000} \quad (3-14)$$

Where; Relative atomic mass of sulphur = 32 and Molar mass of sulphate = 96

3.2.3 ANOVA for proximate and ultimate analysis of samples

ANOVA allowed us to compare the means of different biomass samples. This enabled us to identify statistically significant differences among them. This was crucial for understanding variations in characteristics like moisture content, ash content, volatile matter, and fixed carbon. Since proximate analysis often involves multiple measurements for each sample. It helped assess the consistency and reliability of these measurements by evaluating variance within and between samples, providing insights into the experimental design's robustness. In industrial applications or research, understanding

whether differences in proximate analysis are statistically significant can influence decisions regarding feedstock selection, processing conditions, or product development. It illustrated the statistical significance of differences among the five distinct food waste samples.

3.3 Simulation and Validation using Aspen Plus.

Aspen Plus is popularly used for the gasification of biomass and simulation processes due to its pre-installed library model for calculating characteristics of solids as compared to other software. Furthermore, numerical calculations are easily performed by a FORTRAN code (an imperative programming language) that simplifies numerical computations. Aspen Plus, a valuable tool in this study, with a comprehensive thermodynamic property database accurately predicted bio hydrogen production. It offered various reactor models and simulated separation and purification processes that are relevant to bio hydrogen production.

3.3.1 Process Simulation Model Development

Error! Reference source not found. highlights a three-phase graphical model comprising phase 1: food waste drying, phase 2: decomposition, combustion, and reduction; and phase 3: hydrogenation. Phase 1 was accelerated by a compressor supplying hot air into the dryer. Phase 2 transformed dried food wastes into constituent elements through combustion, oxidation, and reduction at elevated temperatures. Reforming and water gas shift reactions followed sequentially before cooling the system and separating the gases and condensate in phase 3. Pressure Swing Adsorption purified hydrogen from the stream and flashed impurities like hydrocarbons and carbon oxides. Hydrogen gas is then separated from tail gas at the end of the system.

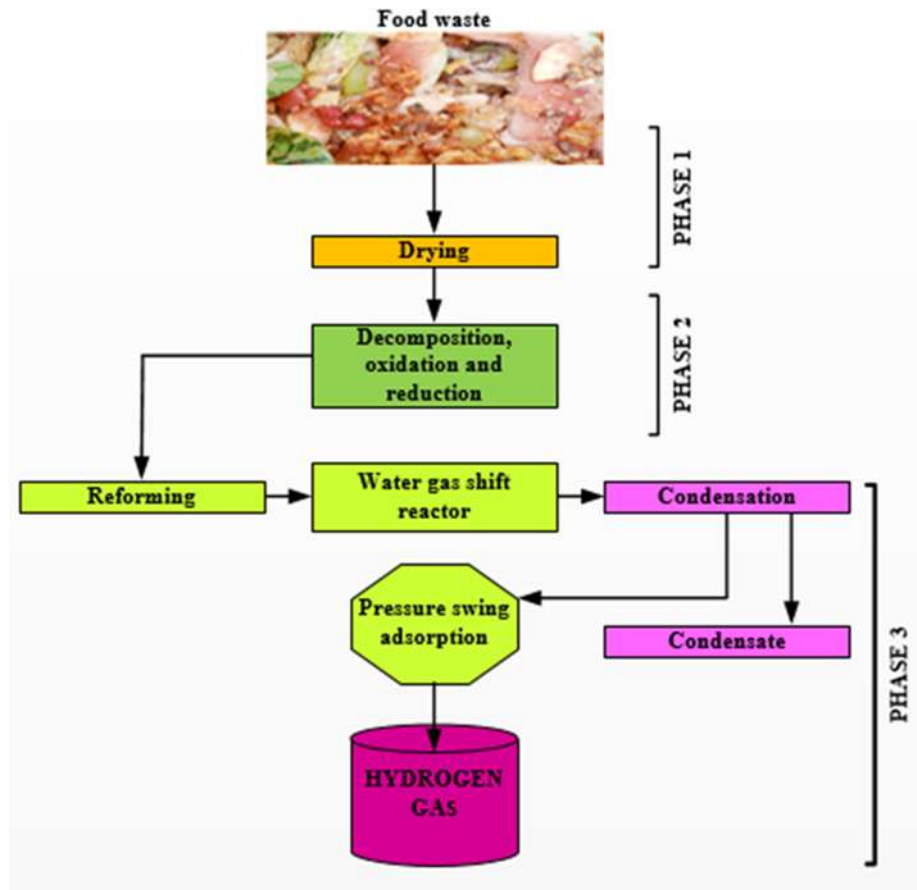


Figure 3-2: Graphical presentation of the simulation process

Feedstock like food wastes and Ash are excluded from the database of the standard components of Aspen Plus Software. This resulted in specifying the universal stream class as MIXCINC containing NC, CISOLID, and MIXED sub-streams, associated with modeling ash and biomass materials like food that are non-conventional (Kombe et al., 2022). Peng- Robinson state equation was used to simulate the Non-Conventional (uncommon) components' physical properties in the properties environment of the software (Kombe et al., 2022).

3.3.2 Model Flow Sheet Description

The simulated flow sheet for the food waste gasification process is shown in Figure 3-3. The red-marked streams are the feed and intended product of the system. The software's reactor block and streams used in the study and their operating conditions are described in Table 3-1 using 'user-assigned' as well as the software developer's names.

3.3.3 Simulation Procedure

The key Non-Conventional Biomass Components for this study were first stated as wet and dry food wastes (WETFW, DRYFW) as well as ASH, while conventional ones were identified as air, water, methane, carbon dioxide, carbon monoxide, sulfur, oxygen, nitrogen, and hydrogen. The 'B1-DRIER' block in the flow sheet simulated food waste drying for moisture content reduction. The moisture calculator was introduced to control the drying process. The excess moisture was flashed by a separator block B2-FLSHT to get the dried food waste (DRYFW). The dried food waste was thermally decomposed to its conventional components in a yield reactor block B3-DECOM. The disintegration was achieved by specifying the distribution of the yield in a calculator block via a FORTRAN statement based on the feedstock's proximate and ultimate analysis results.

The decomposed food waste (FWDECOMP) was then mixed with air in the RGibbs reactor block (B4-PYROL) for oxidation. A second RGibbs reactor block (B5 GASF2) simulated the gasification of decomposed food wastes. The reactors B4-PYROL and B5-GASF2 determined the syngas composition through Gibbs free energy minimization by specifying the operating conditions in Table 3-2-2. An SSplit block (B6-CYCLO) separated ash and carbon solids from syngas. Steam and gas product (GAS-P) was mixed in the B7-MIXER block, followed by steam reformation of methane in an Rstoic reactor block (B8-REFOM) and RGibbs reactor block B9-RGIBB. The temperature of the resultant syngas stream (REF-P) was lowered from 600 °C to 265 °C in a cooler block (B10-H1), allowing water gas shift reactions to take place in a stoichiometric reactor block (B11-WGSR). Condensation of the reacted products to a temperature of 35 °C occurred in Cooler block (B12-H2) to allow the removal of water through a flash block (B13-FLSH). The separation of hydrogen from the remaining gases was finally achieved by a Pressure Swing Adsorption in the Separator block (B14-PSA).

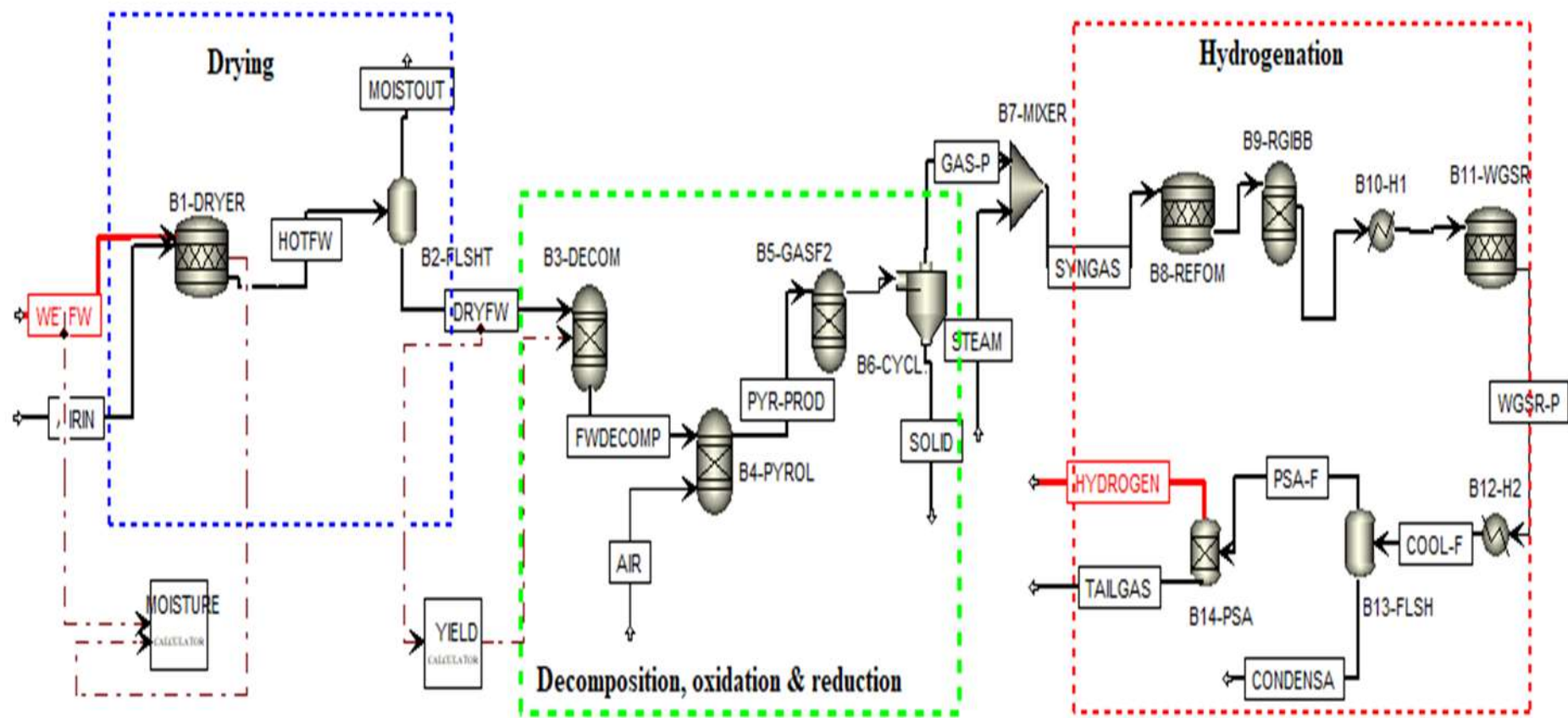


Figure 3-3 : Food waste gasification model flow sheet for hydrogen generation in Aspen Plus

Table 3-1: Definition of blocks and their conditions

Conditions					
User's Block ID	Developers' Default ID	Temperature (°C)	Pressure (bar)	Phase	Description
B1-DRYER	Rstoic		1		To simulate wet food waste drying by specifying executable Fortran statements
B2-FLOUT	Flash2		1	Vapor-Liquid	To separate excess moisture from dry food waste.
B3-DECOM	RYield	550	1		Decompose food waste into its conventional components via definition of yield distribution based on proximate and ultimate analysis results in a yield calculator
B4-PYROL	RGibbs	550	1	Vapor - Liquid	Model oxidation of the disintegrated food waste
B5-GASF2	RGibbs	800	1	Vapor-liquid	Simulate food waste gasification
B6-CYCLO	Ssplit				Simulate solid separation from syngas.
B7-MIXER	Mixer	550	1	Vapor-Liquid	Mix steam and syngas
B8-REFOM	Rstoic	600	10	Vapor-	Simulate steam reforming of Methane $(\text{CH}_4 + \text{H}_2\text{O}) = (3\text{H}_2 +$

				Liquid	CO).
B9-RGIBB	RGibbs	600	10	Vapor- Liquid	Simulate dry reforming by converting methane into synthesis gas and clean liquid fuels
B10-H1	Heater	265	10	Vapor- Liquid	Reformed product's temperature is lowered in preparation for water gas shift reactions.
B11-WGSR	Rstoic		10	Vapor- Liquid	Duty = 0 kW; 0.75 fractional Conversion. (CO + H ₂ O) = (H ₂ + CO ₂)
B12- H2/COOLER	Heater	35	8	Vapor- Liquid	Simulate the cooling process from 265 °C to 35 °C for water removal via flash
B13-FLSH	Flash	35	8	Vapor- Liquid	Separate vapor liquid mixtures of hydrogen and carbon dioxide
B14-PSA	Sep				Simulate Hydrogen separation from mixed gas

Table 3-2: Model feed stream and their operating conditions (Kombe et al., 2022)

Feed Stream ID	Configurations		
	Temperature (°C)	Pressure (bar)	Flow rate (Kg/hr)
WETFW	28.55	1	20
AIRIN	146	1	80
AIR	28.55	1	20
STEAM	105	1	10

3.3.4 Model assumptions

Modeling assumptions for this study were as follows:

- a) Decomposition and pyrolysis stages occur simultaneously as the feedstock is subjected to heat in a dynamic, continuously changing environment with varying temperatures (Wang et al., 2024).
- b) The reactions' residency time in the gasifier is sufficient for both chemical and thermodynamic equilibrium conditions to be achieved.
- c) Ashes are inert
- d) The gas products CH₄, CO, CO₂, H₂, and N₂ by the Peng-Robinson state equation accompanied by the Boston-Mathias alpha function (Kombe et al., 2022)
- e) There is an assumption that the gasification process is a steady state with constant pressure (Carmona et al., 2024)
- f) Char is regarded as Carbon that is graphitic

3.3.5 Sensitivity Analysis Procedure

Computation of sensitivity analysis was done by varying the gasifier temperature from 450 °C to 900 °C, air-to-fuel ratio (A/F) from 0.0 to 2.5, and steam-to-biomass ratio (SBR) from 0.25 to 6.25. The effect of temperature, A/F, and SBR on hydrogen flow rate, yield, and syngas composition was then studied. It should be noted that the percentage of hydrogen yield was obtained from the ratio of the specific mass flow rate of hydrogen to biomass feedstock flow rate according to equation 3-15 (Safarian et al., 2021).

$$\text{Hydrogen gas yield (\%)} = \frac{\text{Hydrogen gas flow rate } \left(\frac{\text{kg}}{\text{hr}}\right)}{\text{Biomass feed stock flow rate } \left(\frac{\text{kg}}{\text{hr}}\right)} \times 100 \quad (3-15)$$

3.3.6 Model Validation

The simulation model was authenticated using published experimental results of Jayah et al. (Jayah et al., 2003) and simulated results of Kombe et al., (2022) obtained under similar conditions as the performance boundaries of the simulation. The Root Mean Square Error (RMSE), determined using equation 3-16 (Aydin et al., 2018), was used to quantify the deviation between the published experimental results of Jayah et al., (2003), the simulated results of Kombe et al., (2022), and the simulated results of this study, with an acceptable deviation range of 10-20% (Sultana et al., 2023).

$$RMSE = \sqrt{\sum_{i=1}^N \frac{(\text{Experimental } i - \text{Model predictions } i)^2}{N}} \quad (316)$$

Where N = the number of data sets

3.4 Response Surface Methodology (RSM) analysis and optimization procedure

Minitab 18 software was used to create a custom response surface design matrix with 337 test runs from the simulated results for analysis and optimization. Temperature, AFR, and SBR were selected as continuous factors where low and high values were chosen by the system using the data in the worksheet. A two-level factorial was chosen

for the 3 continuous factors, and cumulative hydrogen yield in percentage was presented using equation 3-17 by Bayuo et al. (2020).

$$T = d_0 + \sum_{i=1}^n d_i X_i + \sum_{i=1}^n d_{ii} X_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^n d_{ij} X_i X_j \quad (317)$$

Where: T = hydrogen yield, d_0 = coefficient constant, d_i = linear coefficient, d_{ij} = coefficient of interactions, d_{ii} = quadratic coefficient, and X_i, X_j = coded values of coefficients.

3.4.1 Analysis of Variance

Analysis of Variance (ANOVA) was conducted for significance investigation of the model while variables for hydrogen yield were based on coded units. Regression analysis helped in interpreting residuals. This enables the designer to determine how well the model fits before drawing contour/ surface plots. R-squared measured the proportion of variance in response variable helping evaluate model adequacy in Response Surface Methodology (RSM) using the following steps:

- a) Design Experiments-
- b) Collect data
- c) Fit model
- d) Analyze model
- e) Optimize

Contour and response surface plots were employed to investigate the compound effects of temperature, A/F, and SBR on hydrogen yield. The plots were used to obtain the variables' optimal values within the range of the study. Response Surface Analysis involved initially searching for the region containing the optimum and performing a thorough search of the region where the optimum was believed to be. This region was zoomed in for the identification of optimum points.

3.5 Economic Analysis

For proper decision-making on the viability of the system process, a cost-benefit analysis was done by considering the total system costs with capital recovery factor, fixed and variable operation and maintenance costs, the current electricity price, and the hydrogen output of the system in kg/hr. Since the future values were unpredictable and different

from the present value, future discounted values were predicted using the present costs and benefits as expressed in Equation 3-18 (Garrison et al., 2021).

$$PV = \frac{FV}{\left(1 + \frac{r}{100}\right)^n} \quad (3-18)$$

Where, PV - Present value, FV - Future Value, r - discount rate, and n - period

Capital investment included the cost estimates of equipment and materials obtained from the literature, but based on Kenyan market price estimates. Total operation and maintenance (O&M) costs were fixed, and variable costs were expected to be incurred during plant operation. They consisted of the costs of auxiliary equipment, such as compressors, pumps, and electric motors, which enable the balance of plant (BOP). Chemicals, utilities, research, and development are also part of these costs (Indrawan et al., 2020). The equipment and material cost estimates for a small-scale hydrogen generation plant producing approximately 2.5 kg/hour of hydrogen is captured in Table 3-3

Table 3-3: Equipment and material cost estimates of the system

System Unit	Equipment/Item Description	Unit Cost (USD)	Remarks
1 Drying Unit	Drier	971.25	Local
	Compressor (Air, Steam)	1,923.075	Imported
	Belt Conveyor	1,923.075	Imported
2 Decomposition/ Pyrolysis	Reactor, Cyclone Separator, Control System	11,539.95	„
	Ash elimination system (Ash drum, screw conveyor, electric motor)	1,923.075	„
3 Hydrogenation	Syngas cleaning System (Gas scrubbing system, pump), Condenser, PSA, H ₂ gas generation and collection system	12,500	„
Total		30,780.425	

3.5.1 Net Present Value (NPV)

The NPV measures the effectiveness of an investment by comparing the present value of its expected cash inflows with the current value of its anticipated cash outflows, over a specified period. It is simply the cumulative cash flow (in their present values) during the whole project life (including the construction period) (Dobrowolski & Drozdowski, 2022). A positive NPV suggests the investment is profitable, while a negative NPV indicates that there is no economic value in the project. This was computed in Excel Software using equation 3-19 (Abdelhady, 2021).

$$NPV = \frac{T_1}{(1+r)^1} + \frac{T_2}{(1+r)^2} + \frac{T_3}{(1+r)^3} + \dots + \frac{T_n}{(1+r)^n} - \text{Initial investment} \quad (319)$$

Where: T_1 , T_2 , T_3 and T_n = Net flow of cash during first, second, third and n^{th} year respectively; r = discount rate; n = period

3.5.2 Internal Rate of Return (IRR)

This equalizes the net current value of the costs and benefits estimating the profitability of the project or any potential investment. The current value of the expected cash inflow is equal to the opening cash outflow. For the project to be acceptable, the IRR should be greater than the discounted rate of capital cost. If IRR is less, then it is advisable to decline the project and if IRR is equal to the discounted rate and, then the decision is not defined. IRR was computed in Excel Software using equation 3-20 (Nouwe Edou & Onwudili, 2022)

$$IRR = S1 - C1 \times \frac{S2-S1}{C2-C1} \quad (3-21)$$

Where: IRR = Internal Rate of Return; $S1$ = Percentage value that yields a positive NPV, $S2$ = Percentage value that yields a negative NPV, $C1$ = Positive NPV and $C2$ = Negative NPV

3.5.3 Simple Payback Period (SPBP)

This is a simple metric that evaluates investment projects based on how long the initial capital will be recovered through the project's cash inflows. This is the time the project will reach the breakeven point (Sinaga et al., 2023) computed in Excel as per the

equation. 3-22. If cash inflows are uneven, the calculation involves accumulating the cash inflows year by year until they balance. A project with a short payback period is often considered less risky because the initial investment is recovered sooner. Equation 3-21 was applied in the Excel software to compute the payback

$$PBP = \frac{\text{Initial Investment}}{\text{Yearly cash flow}} \quad (323)$$

3.5.4 Discounted Payback Period (DPBP)

This incorporates time into the payback period. The short and long-term benefits of the system were assessed using the discounted payback period. Discounted payback period is the time it will take to recover the invested finances as indicated in equation 3-24 (Kiran, 2022). Discounted cash flows are accumulated year after year until the sum equals to the initial investment.

$$DPBP = \frac{C_1 - C_s}{C_a} \quad (3-25)$$

Where: C_i = Initial Invested cash, C_s = Final system closing value, C_a = Average annual cash flow.

If the DPBP is shorter than or equal to the pre-established acceptable limit, then the investment is considered acceptable.

DPBP is always longer than the PBP since it accounts for the net present value of money. Future cash inflows are worthless in present times.

3.5.5 Profitability Index (PI)

The Profitability Index is the payoff ratio of an investment that estimates the project's attractiveness. A PI greater than 1 indicates that the project is expected to be profitable, with a higher index indicating a more attractive investment opportunity. A PI of exactly 1 shows that the project is anticipated to break even, while a PI less than 1 suggests that the project may not be profitable and should be avoided. The PI was calculated using equation 3.23 (Shahbeig & Nosrati, 2020).

$$PI = \frac{\text{Net present value}}{\text{Total system costs}} \quad (326)$$

3.5.6 Economic Analysis assumptions

Microsoft Excel software was used in the economic analysis with the following assumptions.

- a) Food waste was not purchased.
- b) The Inflation rate was subjective.
- c) Average KES/USD exchange rate was KSh 130/USD.
- d) The lending interest rate was 12%-15% depending on commercial bank (Source: Central Bank of Kenya).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physical and Biochemical Characteristics of the Sampled Food Wastes

4.1.1 Moisture Content (MC)

Optimizing moisture content is crucial for efficient gasification since high moisture content reduces the energy efficiency of the gasification process, as energy is consumed to evaporate water. Typically, feedstocks with lower moisture content (< 20-30%) are preferred for gasification (Rajasekhar Reddy & Vinu, 2017). Figure 4-1 illustrates the moisture content in food waste samples as they were being prepared for hydrogen production. It was observed that the dry food wastes in Sample 2 registered the lowest MC at 5.1% while Sample 5 had the highest MC at 6.51%. From the error bars, the results revealed a significant difference in the means of the samples.

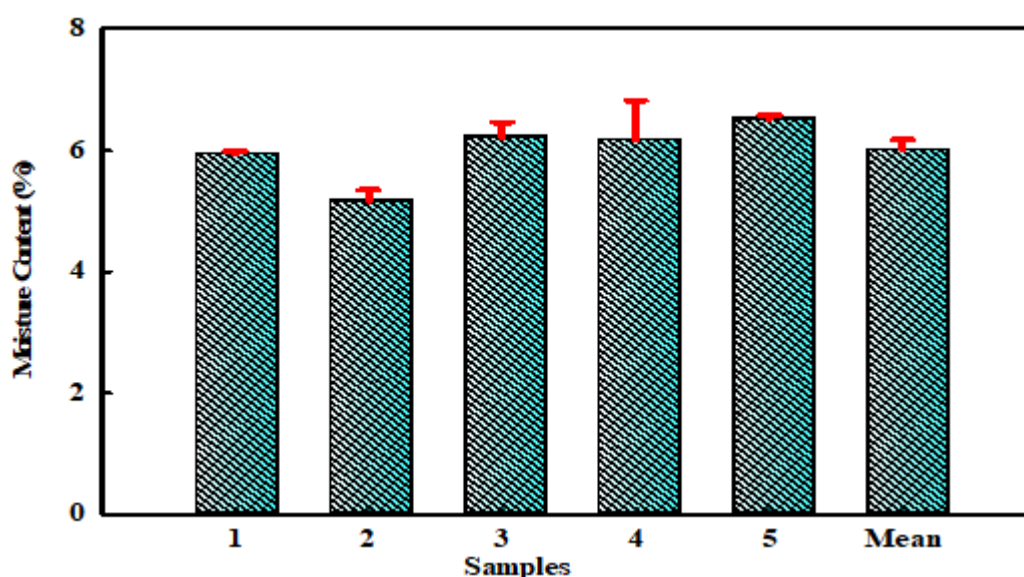


Figure 4-1: Moisture content results

Food wastes from hotel industry require proper drying before gasification. Under 10% moisture content is recommended if better endothermic reactions such as gasification and pyrolysis is to be achieved. This involves conversion of food wastes into carbon monoxide and hydrogen (Abdalla et al., 2018). During the syngas production from biomass gasification study by Gao et al. (2023), moisture content affected the composition of the syngas produced. The findings as outlined in the previous studies highlight that moisture content above 10% can dilute the gas decreasing hydrogen concentration as water vapor competes with carbon monoxide and methane during

gasification processes. This implies that food waste from the hotel industry with an approximate 6% moisture content can undergo gasification reactions generating a reasonable amount of hydrogen.

4.1.2 Total Solids (TS) and Volatile Solids (VS)

Total and Volatile Solids are crucial parameters in the gasification process. TS and VS determine the suitability of a feedstock for gasification, and they are key in the process optimization. Figure 4-2 illustrates the TS and VS content of food waste for hydrogen production. The total and volatile solids were observed to range from 93.23 - 94.06% and 81.57 - 86.86% as shown in Figures 4-2 (a) and (b), respectively.

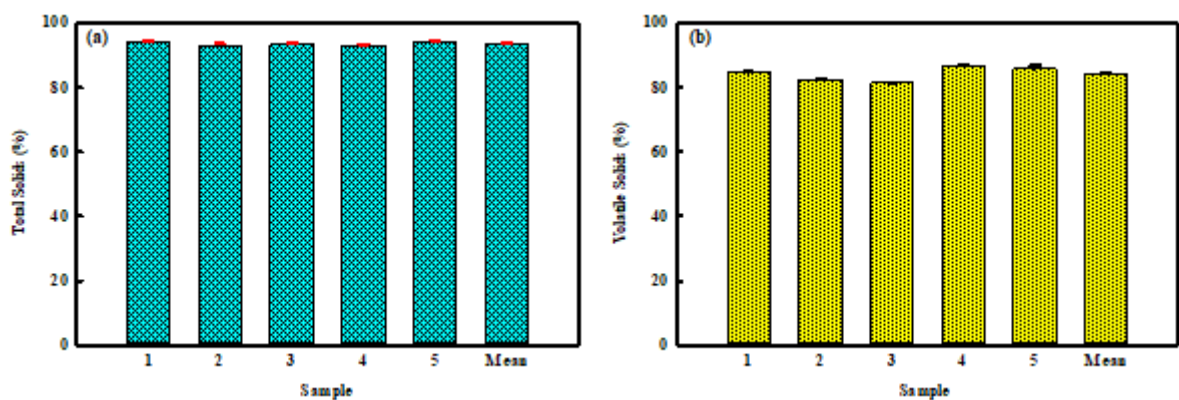


Figure 4-2: Total and Volatile results

A statistically significant difference in the means for TS and VS was observed as depicted from the error bars. TS and VS parameters are critical in syngas generation through thermal waste-to-energy conversion processes. The biohydrogen production rate and production potential are dependent on the high organic matter in the food wastes (Mrosso et al., 2023). Havilah et al. (2022) observed that a higher TS improves the gasification efficiency as it provides feedstock for the gasification reactions. With TS and VS ranges of 93.23 - 94.06% and 81.57 - 86.86% respectively, this study implies that food waste from the hotel industry can produce considerable amounts of hydrogen. It is evident from the literature that higher TS content frequently leads to a higher heating value, which can enhance the overall energy yield from the gasification process. Biomass with higher TS may have better reactivity due to a high proportion of lignocellulosic material, facilitating more efficient gasification reactions and improving hydrogen yield (Cortazar et al., 2023; Güleç et al., 2022; Qin et al., 2022). Therefore, managing TS content is crucial for hydrogen production via air gasification. This can be achieved

through balancing feedstock availability (Taipabu et al., 2022), gas quality (Mankasem et al., 2024), and operational efficiency (Hassan et al., 2024).

A higher VS content generally means more volatile compounds are available for conversion into gaseous products, enhancing the overall efficiency of gasification and increasing hydrogen yields (Koshariya et al., 2024; Xu et al., 2022). As Etezadi et al. (2023) put it, VS contributes to the formation of syngas (a mixture of hydrogen, carbon monoxide and methane) during gasification. Higher VS in this study (81.57 - 86.86%) is desirable for pyrolysis conversion of food wastes into syngas composition with higher hydrogen concentrations. This range of VS Content in Food Wastes positively influences gasification reactions, enhancing process stability and improving hydrogen production yield. It is further observed that high organic matter, ranging from 80% to 95%, means a high volatile solid content, which is critical for hydrogen production (Xie et al., 2022).

4.1.3 Ash and Fixed Carbon

Ash is significant during the gasification process for bio-hydrogen production since it has catalytic effects on the reactions, potentially influencing tar formation and gas composition. High ash content can lead to operational problems such as slagging, fouling, and agglomeration, which reduce gasifier efficiency and longevity. The amount of fixed carbon in the feedstock can impact hydrogen yield, as it influences the extent of gasification reactions. Figure 4-3 illustrates the percentage of ash and fixed carbon in food waste samples. It shows a minimal presence of solid residue (ash and fixed carbon) ranging from 2.25% - 7.32% and 9.73% - 14.82% respectively. Samples 3 and 5 had the highest ash content (7.8%) and fixed carbon (14.8%) as highlighted in Figure 4-3 (a) and (b) respectively. This is basically due to the heterogeneous nature of food waste.

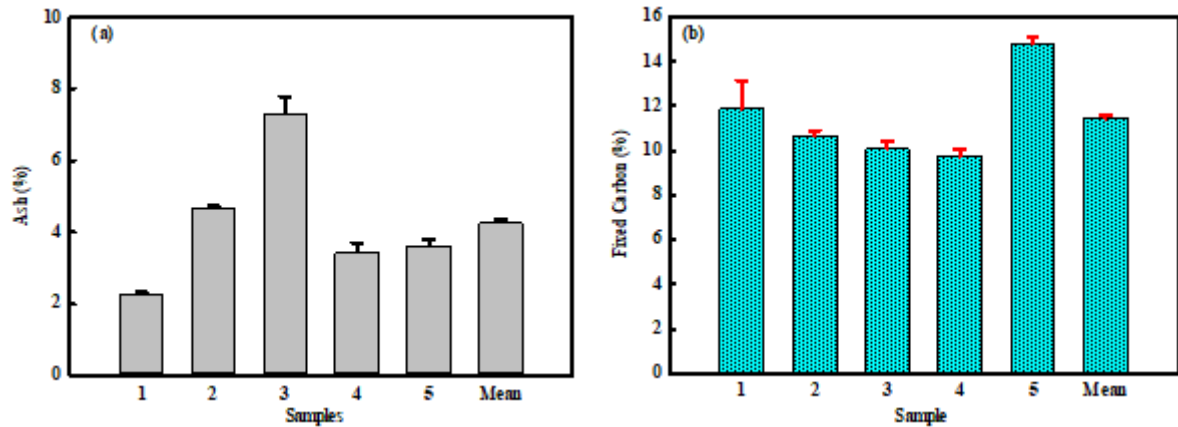


Figure 4-3: Ash and Fixed Carbon content

Nikiema et al. (2022) observed that food waste samples with ash content less than 4% and fixed carbon from 9% to 25% could have great potential in syngas generation enhancing hydrogen production. There is an occasional wide range of variation of ash and fixed carbon with a coefficient of variation above 50% as seen in samples 1 and 3 in Figure 4-3 (a) and samples 4 and 5 in Figure 4-3(b) respectively. Ash content above 10% can reduce the overall gasification efficiency lowering hydrogen yields (Pour & Makkawi, 2021). Since Ash does not contribute to the production of combustible gases, it can dilute the biomass feedstock, leading to lower hydrogen yields. Czerski et al. (2021) observed that the thermal and catalytic properties of the gasification process can also be affected by ash content exceeding 10% in biomass. This implies that the minimal amount of ash (4.5%) from this study will be available to absorb heat and lower the overall temperature in the gasifier, which may hinder the gasification reactions necessary for producing hydrogen (Zhou et al., 2023). Sample 1 promoted hydrogen production as compared to Sample 3 as stated by Cao et al. (2020), since low ash content like in this study is preferred to maximize energy output and minimize operational challenges. Some studies suggest that certain types of ash can aid in carbon capture during gasification, potentially improving the overall sustainability of the process (Li et al., 2021; Mukherjee et al., 2020).

Fixed carbon is a major contributor to the energy content of biomass (Yang et al., 2020). Samples 1 and 5 [Figure 4-3 (b)] enhanced the efficiency of the gasification process improving the overall energy yield. It is evident from previous studies that fixed carbon is converted into syngas during gasification, particularly into carbon monoxide and

hydrogen. A higher fixed carbon content from Sample 5 can result in a greater production of these gases, thereby increasing hydrogen yields (Khairy et al., 2024; Lubwama et al., 2020; Qian et al., 2020). Sample 5 could also stabilize reactions during gasification processes, as indicated by Lee et al. (2021). This can help maintain consistent feedstock characteristics during gasification, contributing to a more stable and controllable process. Comparing the five samples, Sample 5 could still play an important role in carbon conversion efficiency during the gasification process since it has a good proportion that can be converted into syngas impacting the overall hydrogen production (Zhang et al., 2020).

4.1.4 Nitrogen and Total Organic Carbon (TOC)

Balancing Nitrogen and TOC levels is vital for efficient biohydrogen production since nitrogen can positively and negatively affect biohydrogen production using the gasification process. Nitrogen can help reduce tar formation during gasification, potentially improving gas quality (Hwang et al., 2021). It is noted that nitrogen affects gasification temperature, which can impact reaction kinetics and product composition (Shen et al., 2022). On the other hand, TOC plays a significant role in biohydrogen production. TOC is converted into syngas, implying that higher TOC can lead to higher hydrogen yields as more carbon is available for conversion. Figure 4-4 illustrates the percentage of nitrogen and total organic carbon in food wastes for hydrogen production. Figure 4-4 (a) indicates the presence of nitrogen in various food waste samples, ranging from 1.8% to 6.9%.

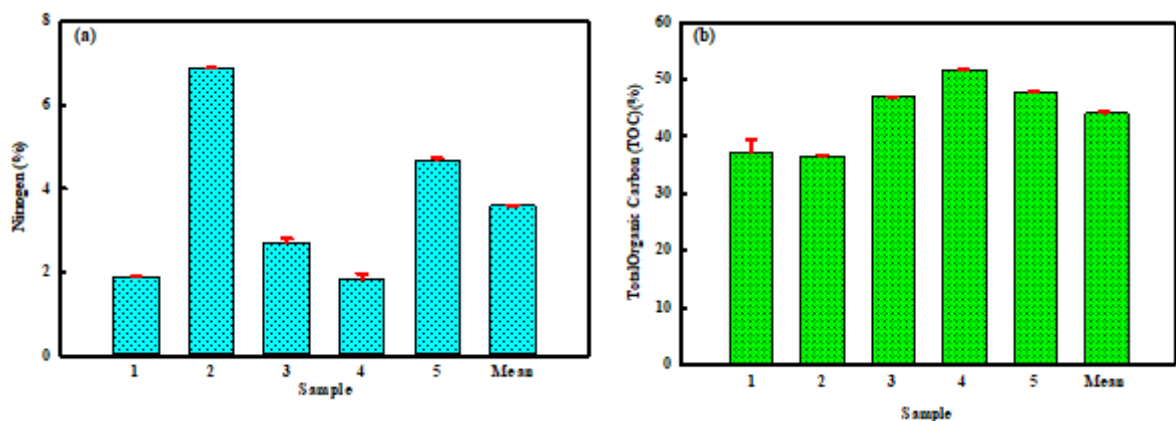


Figure 4-4: Nitrogen and Total Organic Carbon results

Figure 4-4 (a) shows that sample 2 had the highest content of nitrogen at 6.9% while sample 1 had the least at 1.8%. Nitrogen is generally considered an inert component in the gasification process. Its presence does not contribute to hydrogen production or the formation of valuable syngas components, potentially diluting the overall gas output. It is also noted that high nitrogen levels can lead to a lower quality of syngas by increasing the volume of non-combustible gases. This dilution can decrease the concentration of hydrogen and carbon monoxide, which are critical for efficient energy recovery and downstream applications. The results of this study implied that Sample 2 could lower syngas quality as compared to Samples 1 and 4 respectively, since it increased the presence of nitrogen which could absorb heat potentially lowering the temperature required for the optimal gasification process, thereby reducing reactivity and lowering hydrogen yields. A similar observation was made by Cerone et al. (2020).

Figure 4-4 (b) highlights the percentage range of 35-54% TOC present in food waste from the hotel industry. Comparing this study with the organic waste gasification review by Frolov, (2021), it was observed that Samples 3, 4, and 5, with higher TOC enhanced gasification process improving hydrogen production due to high conversion of carbon into syngas components. It is also noted that the efficiency of the gasification process often correlates with TOC (Samimi et al., 2020). A higher TOC in Sample 4 will lead to better conversion rates, resulting in a more effective process for producing hydrogen. Sample 2 may not have provided sufficient organic material for optimal gasification since it had low TOC. TOC influences feedstock quality (Temel, 2023), gasification efficiency (Marcantonio et al., 2020), syngas composition (Segneri et al., 2022), and overall process dynamics. Managing TOC levels effectively can enhance hydrogen yields and the viability of the gasification process.

4.1.5 Carbon to Nitrogen (C/N) ratio

Another important parameter to consider during gasification process is the C/N ratio. While it might not be the primary factor controlling biohydrogen production in the gasifier, it can have indirect effects on process performance and efficiency. Optimizing C/N ratio might be beneficial in feedstock blending with different C/N ratios to achieve optimal gasification performance.

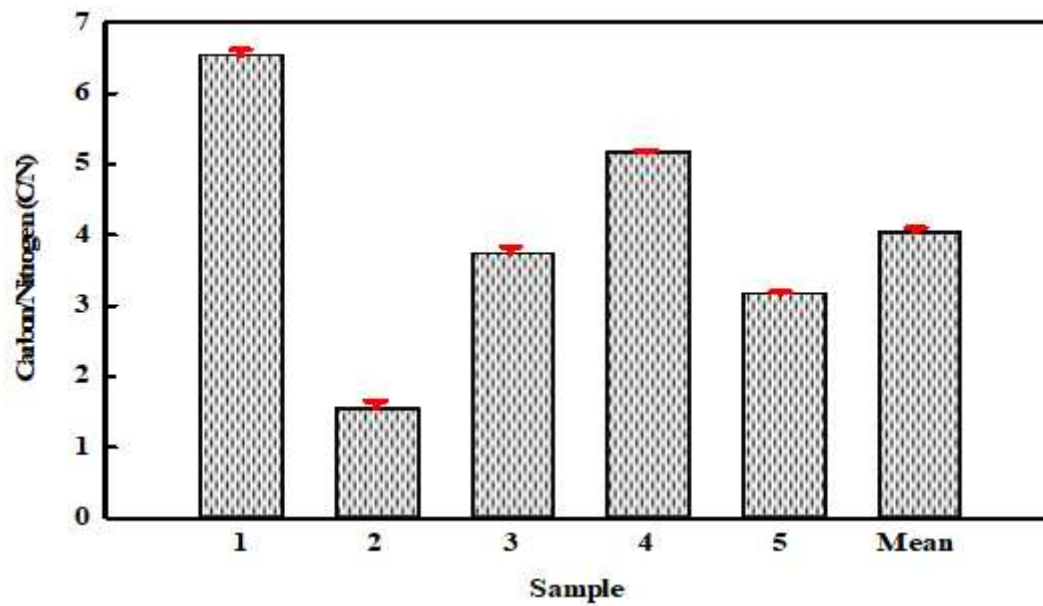


Figure 4-5: Carbon to Nitrogen ratio results

Figure 4-5 shows the carbon-to-nitrogen ratios in food waste samples. The C/N ratios for the samples ranged from 1.5 (sample 2) to 6.8 (sample 1). Sample 1 with a higher C/N ratio of 6.8 generally indicates a greater proportion of carbon relative to nitrogen, which is beneficial for gasification as compared to Sample 2 with a lower C/N ratio of 1.5. Sample 1 can lead to improved conversion efficiencies, as more carbon is available to produce syngas components (Mu et al., 2024; Zhang et al., 2023). It is prudent to maintain an appropriate C/N ratio of 6.8 to 7.4 as it can enhance the quality of the produced syngas (Ghaleb et al., 2021). As temperature increases in the gasification process, so does the increased availability of carbon which can increase the concentrations of hydrogen and carbon monoxide. Conversely, excess nitrogen can dilute these valuable gases, lowering overall syngas quality (Rey et al., 2024). During the microdynamics of biomass steam gasification study by Zou et al. (2024), it was observed that the C/N ratio influences the reaction dynamics within the gasifier. A balanced ratio can enhance the kinetics of the gasification reactions, leading to faster conversion rates and higher hydrogen yields. High nitrogen levels can hinder these reactions, slowing down gasification processes.

Considering thermal characteristics, nitrogen, being inert, can affect the thermal dynamics within the gasifier. A lower C/N ratio may result in lower temperatures (Schmid et al., 2023) and reduced thermal efficiency (Wattana et al., 2020), negatively impacting hydrogen production. Maintaining an appropriate C/N ratio contributes to the stability of the gasification process. An imbalance, particularly with high nitrogen content, can lead to fluctuations in gas composition and temperature, complicating process control and reducing efficiency. There is often an optimal C/N ratio for biomass gasification, typically ranging from about 20:1 to 30:1 for many feedstocks (Capareda, 2022). Ratios significantly outside this range like in this study (1.5 to 6.8), can lead to reduced hydrogen yields and increased operational challenges. Considering tar formation during biomass gasification processes, it is believed that a higher C/N ratio may help in minimizing tar formation during gasification (Wang et al., 2022). Tar can be problematic for downstream processing, so optimizing the C/N ratio can contribute to cleaner syngas production. In summary, the carbon-to-nitrogen ratio is crucial for optimizing hydrogen production via air gasification. It affects gasification efficiency, syngas quality, reaction kinetics, and overall process stability. Managing the C/N ratio effectively can enhance hydrogen yields and the viability of the gasification process.

4.1.6 Crude proteins and lipids

Proteins are a primary source of nitrogen in biomass (Leng et al., 2020; Zong et al., 2020). This implies that high protein content leads to an increased nitrogen content, which may dilute the syngas produced during gasification and reduce hydrogen yields hence, the need for an optimal balance to maximize hydrogen production. During the gasification process, sample 2 with a protein content of 43% could decompose faster into various gaseous products, including ammonia and other nitrogenous compounds than Sample 1 (11.36%) (Wang et al., 2022). These byproducts can affect the overall composition of the syngas, potentially lowering the concentration of valuable gases like hydrogen. It is also noted by Ong et al. (2020) that the presence of proteins in food wastes can impact the thermochemical reactions in the gasifier. While some proteins can be beneficial for enhancing reactivity, too much (above 50%) can disrupt the gasification process and lower hydrogen yields (Heeley et al., 2024). In summary, this study implies that proteins in samples 1, 2, 3, 4, and 5 influence hydrogen production via air

gasification by affecting nitrogen content, syngas composition, and thermochemical reactivity.

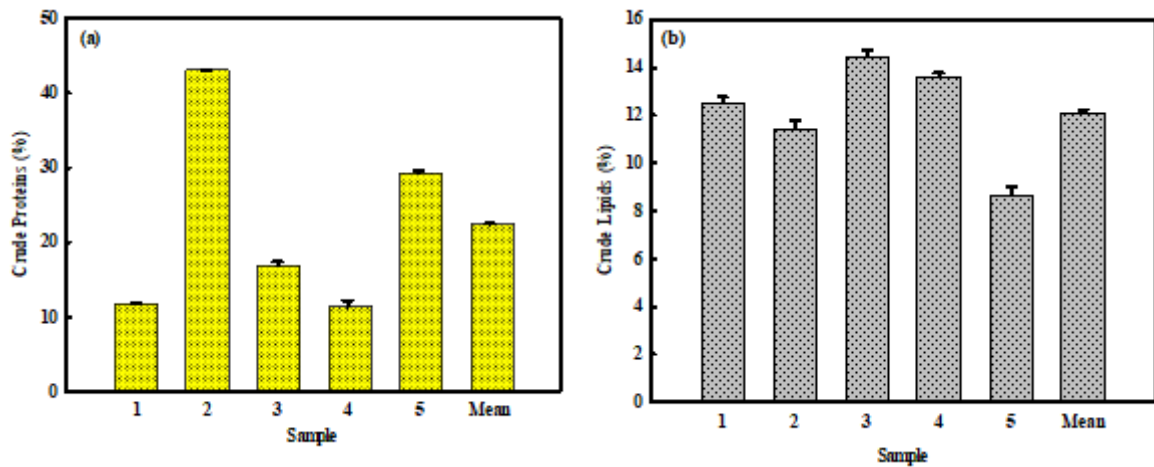


Figure 4-6: Crude proteins and lipid results

The current progress in the production technologies of lipid-based biofuels indicates that lipids have a high energy density, contributing to the overall calorific value of biomass (J. Wang, Singer, et al., 2022). This implies that high crude lipid content in Sample 3 could enhance the energy yield during gasification, favoring hydrogen production when properly converted. The lipids in the food waste decompose into lighter hydrocarbons and gases leading to a syngas rich in hydrogen. Sample 3 (15%) could break down easily compared to sample 5 (8%) since the reactivity of biomass can be enhanced by lipids. During the gasification process, lipid breakdown can help maintain temperature and promote favorable conditions for hydrogen production as alluded to by Aboeela et al., (2023).

4.1.7 Potassium, Sodium, Calcium, and Phosphorus

Understanding the roles of potassium, sodium, calcium, and phosphorus elements is crucial for optimizing feedstock selection, gasification conditions, and ash management. They impact gasification efficiency by influencing kinetic reactions and catalyst activity. Figure 4-7 highlights the presence of potassium, sodium, calcium, and phosphorus in food wastes for hydrogen production. The minimal content of potassium in food waste samples ranged from 0.2% to 1.56%, the lowest being from sample 3 while the highest being from sample 2. A statistically significant difference in the various groups can be observed from the error bars.

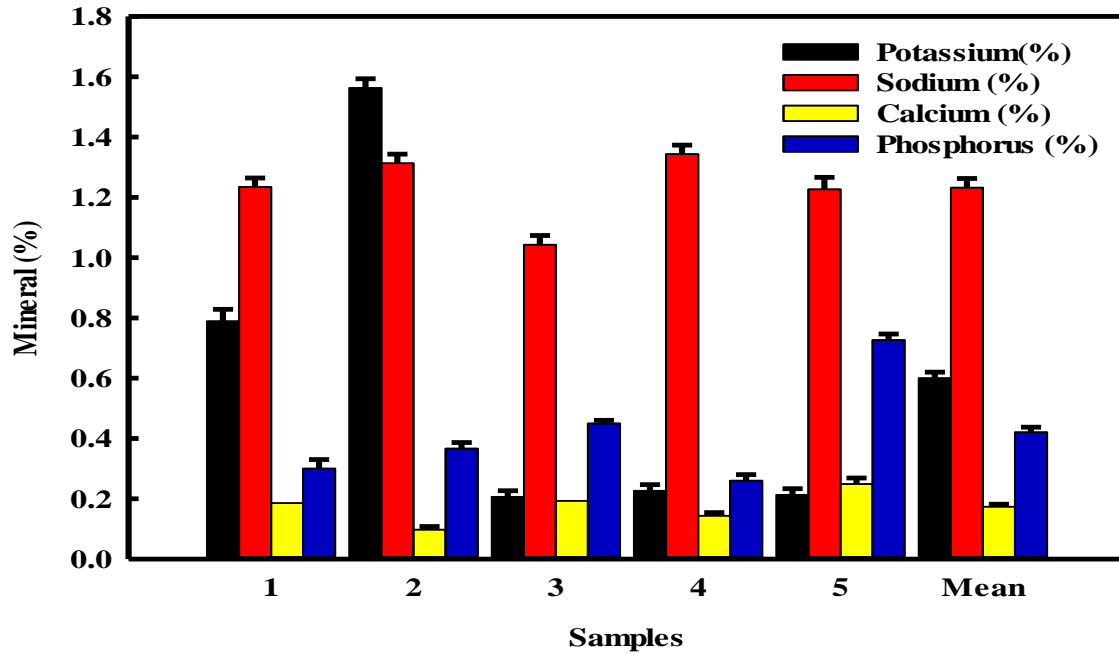


Figure 4-7: Potassium, Sodium, Calcium, and Phosphorus results

Low levels of potassium, as shown in this study (0.2-1.56%), would be linked to the alkaline content in food waste that is highly volatile at the combustion and gasification process as observed by Knutsson et al. (2018). While potassium in its limited content promotes a catalytic effect during the gasification process, Haiping et al. (2017), stated that it consumes volatile fatty acids, improving the biodegradation of protein-rich components, and enhancing dehydrogenation. Potassium in this study, acting as a catalyst during the gasification process can promote the conversion of biomass into gaseous products, potentially increasing the yield of hydrogen and improving gasification efficiency (Acevedo-Paez et al., 2024).

Potassium can enhance the reactivity of biomass leading to a more efficient breakdown of the biomass structure. This facilitates the gasification reactions and potentially increases hydrogen production (Manikandan et al., 2023). Potassium present in the ash produced from food waste gasification can impact the overall efficiency of the gasification process. Similar observations are made by Zhou et al. (2023). While some potassium can enhance gasification, excessive amounts above 0.5% may lead to operational issues, such as increased ash fouling or changes in gasifier performance (Míguez et al., 2021). The amount of potassium in this study (0.2-1.7%) can influence the thermal characteristics of the gasification process. It may help in maintaining optimal

temperatures, which are critical for efficient gasification and hydrogen production (Wang et al., 2023).

Sodium on the other hand also has catalytic properties that enhance gasification reactions. Its presence (1.2-1.5%) may improve the conversion of food waste into syngas, potentially increasing the yield of hydrogen (Chen et al., 2024). While sodium does not contribute directly to hydrogen production, it can influence the proportions of other gases, such as carbon monoxide and methane, which are also important for energy applications. It is important to note that sodium contributes to the ash content of biomass, whose characteristics can impact the efficiency of the gasification process. High sodium levels above 3.5% may lead to changes in melting behavior, affecting slagging and fouling in the gasifier (Yang et al., 2023; Zhou et al., 2023). There is often an optimal range for sodium content in biomass. While some sodium can enhance gasification efficiency, excessive sodium above 10% can lead to operational issues, such as increased ash viscosity and difficulties in maintaining gasifier performance. Considering thermal properties, sodium can influence the thermal dynamics within the gasifier. It may alter the heat transfer characteristics, which can negatively impact the overall efficiency and stability of the gasification processes as indicated by Gao et al. (2024).

Calcium can act as a catalyst by converting 85% of biomass into gaseous products, including hydrogen, during the gasification process (Li et al., 2021). The calcium in this study would facilitate certain reactions that can improve overall gasification efficiency. This observation is in agreement with the previous study (Acevedo-Paez et al., 2024). Considering ash composition and behavior, calcium contributes to the ash content of biomass, influencing its physical and chemical properties. High calcium levels above 0.8% can alter the melting behavior of ash, which can affect slagging and fouling in the gasifier as discussed earlier. This can negatively impact operational stability and efficiency. Calcium influences the quality of the produced syngas. By promoting the conversion of tars and other heavier hydrocarbons into lighter gases, calcium can enhance the hydrogen concentration and increase the yield of other valuable gases in the syngas (Hu et al., 2024). Some studies suggest that calcium may play a role in capturing carbon dioxide during the gasification process, potentially improving the overall sustainability of hydrogen production (Han et al., 2024; Li et al., 2024). This study revealed that 0.1-0.3% calcium in food waste can positively influence hydrogen

production via air gasification by enhancing catalytic activity, improving syngas quality, and stabilizing thermal conditions (Klinghoffer et al., 2015).

Phosphorus is a vital nutrient for plant growth. Its presence in biomass can enhance overall biomass productivity and quality, which can indirectly affect the availability and yield of feedstock for gasification. Phosphorus may exhibit some catalytic properties during gasification, although its role is less pronounced compared to other elements like potassium and calcium. It can potentially facilitate certain reactions, improving the conversion efficiency of biomass to syngas, which can affect the composition of the produced syngas (Yang et al., 2024). While it does not contribute directly to hydrogen production, it can influence the proportions of other gases, such as carbon monoxide and methane, which are important for energy applications. Considering the ash characteristics, phosphorus contributes to the ash content of biomass (He et al., 2023). This implies that the presence of phosphorus can influence the melting behavior and viscosity of ash, enhancing slagging and fouling in the gasifier. Managing ash properties is crucial for maintaining efficient gasifier operation.

4.1.8 Analysis of Variance (ANOVA) and model Summary for characterization results

The *p-values* ranged from 0.00 - 0.05, while the R^2 values ranged from 36.81% - 99.97% in the majority of parameters. These results indicated a statistically significant difference in the means of triplicate measurements for each of the five samples, with a strong positive correlation. The model was adopted as the majority of the *p-values* were < .001 and R^2 values were above 50% influence as shown in Table 4-1.

Table 4-1: ANOVA and model summary of food waste characterization results

Analysis of Variance (ANOVA)						Model Summary			
Source	DF	Adj SS	Adj MS	F-Value	P-Value	S	R ²	R ² (adj)	R ² (pred)
Moisture Content (%)									
Factor	5	147.40	29.4808	46.80	0.000	0.793694	90.70%	88.76%	85.46%
Error	24	15.12	0.6299						
Total	29	162.52							
Total Solids (%)									
Factor	5	56413.6	11282.7	18394.58	0.000	0.783180	99.97%	99.97%	99.96%
Error	24	14.7	0.6						
Total	29	56428.3							
Volatile Solids (%)									
Factor	5	45562.6	9112.53	2390.92	0.000	1.95226	99.80%	99.76%	99.69%
Error	24	91.5	3.81						
Total	29	45654.1							
Ash (%)									
Factor	5	65.69	13.138	4.53	0.005	1.70342	48.54%	37.82%	19.59%
Error	24	69.64	2.902						
Total	29	135.33							
Fixed Carbon (%)									
Factor	5	641.52	128.304	37.33	0.000	1.85393	88.61%	86.23%	82.20%
Error	24	82.49	3.437						

Total	29	724.01							
Nitrogen (%)									
Factor	5	49.77	9.955	2.80	0.040	1.88665	36.81%	23.65%	1.27%
Error	24	85.43	3.559						
Total	29	135.20							
Crude Proteins									
Factor	5	2881	576.3	4.68	0.004	11.0985	49.36%	38.81%	20.87%
Error	24	2956	123.2						
Total	29	5838							
Crude Lipids (%)									
Factor	5	747.02	149.404	39.06	0.000	1.95577	89.06%	86.78%	82.90%
Error	24	91.80	3.825						
Total	29	838.82							
Total Organic Carbon (%)									
Factor	5	13520.5	2704.10	103.56	0.000	5.10998	94.70%	93.78%	92.35%
Error	29	757.2	26.11						
Total	34	14277.8							
Potassium (%), Sodium (%) Calcium (%) and Phosphorus (%)									
Factor	23	122.55	5.3282	10.92	0.000	0.698548	72.35%	65.72%	56.79%
Error	96	46.84	0.4880						
Total	119	169.39							

4.2 Simulation of Biohydrogen Production results

Simulation results provided valuable insights for scaling up of biohydrogen production from food wastes, and other organic materials.

4.2.1 Model validation results

Figure 4-8 and Table 4-2 highlight the comparison between the published experimental results of Jayah et al. (2003) and the simulated results of Kombe et al., (2022) with the simulated results of this study. From Table 4-2, the average RMSE was found to be 2.7888. Kombe et al., (2022) observed an average RMSE of 1.8295 in their comparison with the same experimental runs. The observed RMSEs of this study are within the acceptable range of 10-20% (Cabanlit & Cruz, 2023) since the fluid dynamics and kinetics of gasification systems are neglected in the simulation model of this study. Since H_2 , CO , CO_2 , and N_2 were predicted to a precise degree, minimal forecasting of CH_4 is observed from the figure as depicted by high percentage errors of 99.72, 99.81, 99.55, and 99.24, respectively. Kombe et al. (2022) observed similar behavior when comparing their simulated results. This is due to short residence time leading to the failure of actual gasifiers to achieve thermodynamic equilibrium thereby minimizing CH_4 forecast. Figure 4-8 indicates a high level of accuracy in the prediction of N_2 as A/F increased from 1.86 to 2.37 at a constant MC of 14.7% as shown in Figure 4-8 (a) and (d), then from 1.96 to 2.2 at a constant MC of 16% as shown in Figure 4-8 (b) and (c) as depicted by the low percentage errors. This is due to the increase in the release of nitrous compounds from food waste as temperature increases in the gasifier (Broer & Brown, 2015). The percentage errors obtained for other components of the syngas is as per Table 4-2. Equivalent observations were done by Oliveira et al., (2021). The comparison results show a detailed simulation model in its predictive capability.

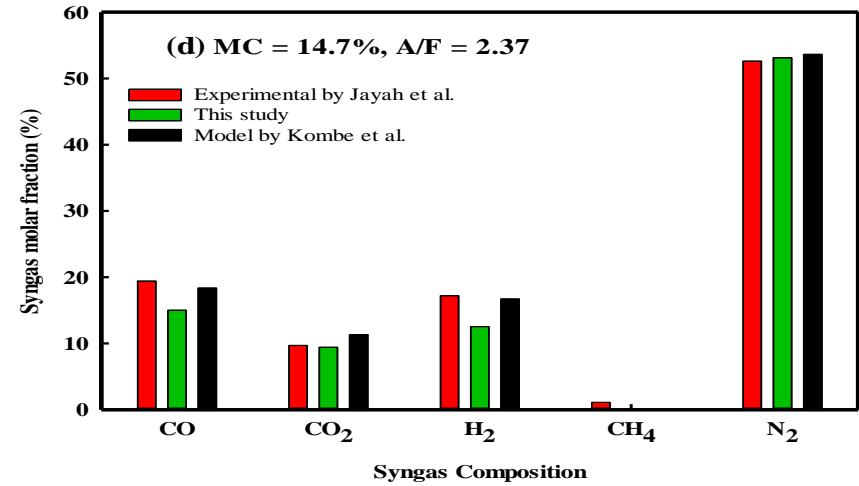
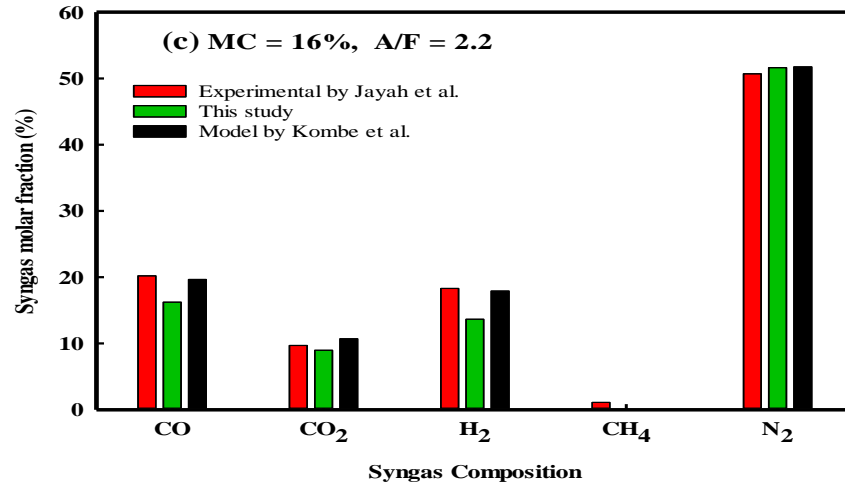
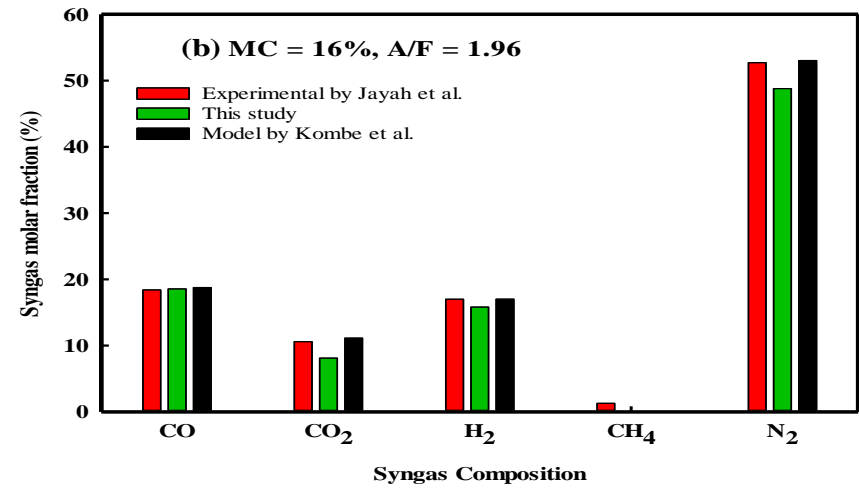
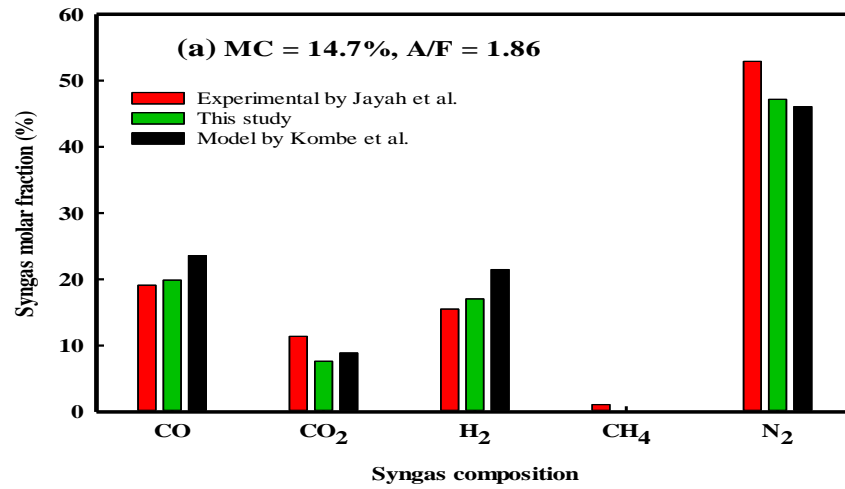


Figure 4-8: Comparison between Aspen Plus simulation Model and experimental results at different MCs and A/Fs

Table 4-2: Comparison between experimental and simulated results

RUN No.	Parameter			% Error (Jayah et al.)				RMSE
	MC (%)	A/F	CO	CO ₂	H ₂	CH ₄	N ₂	
2	16	2.2	19.68	7.48	25.34	99.72	1.83	2.82516
3	14.7	2.37	22.68	2.826	27.08	99.81	0.97	2.91859
4	16	1.96	0.83	23.36	6.98	99.55	7.41	2.21361
7	14.7	1.86	4.06	32.94	10.01	99.24	10.83	3.19772
<i>Average</i>								2.78877

4.2.2 Influence of temperature

Temperature control is crucial for optimizing biohydrogen production, gas quality, and overall process efficiency. Figure 4-9 illustrates the influence of gasifier temperature on the hydrogen flow rate, yield, and syngas composition. From Figure 4-9 (a), a steady increase in hydrogen flow rate from 0.92 kg/hr to 1.07 kg/hr and yield from 4.6% to 5.4% respectively, was observed at the initial temperature rise from 450 °C to 550 °C. This could have been due to the Boudourd, water-gas, and steam reforming reactions, which are endothermic in concurrence with Le Chatelier's principle, which suggests that an increase in gasification temperature enhances the endothermic production of gases. A similar trend was observed by Hussain et al. (2017). It is observed that a further increase in temperature from 550 °C to 900 °C made a minimal difference in the flow rate and yield. This could have been due to sequential chemical reactions taking place. First, the food waste's carbon, which experienced partial oxidation ($C + 0.5O_2 \rightleftharpoons CO$) reaction released heat that fed the gasification reactions. Secondly, food wastes' volatile solid (matter) had degraded into several gases leaving behind the solid containing fixed carbon and ash. The gasses produce synthetic gas (syngas) whose primary components are carbon monoxide and hydrogen.

From Figure 4-9 (b), a steady increase in CO from a mole fraction of 0.02 to 0.31 as temperature increases from 500 °C to 750 °C was observed. This could have been due to partial oxidation reactions in the gasifier. Further increase in temperature promotes water-gas shift reaction ($CO + H_2O \rightleftharpoons CO_2 + H_2$), yielding hydrogen gas. The mole fraction of carbon dioxide decreased gradually from 0.17 to 0.09 as the temperature

increased from 550 °C to 900 °C. This is due to the production of carbon monoxide from Boudouard ($C + CO_2 \rightleftharpoons 2CO$) reactions which took place as temperature increased, thus using up the carbon dioxide (Roncancio & Gore, 2021). There were significant mole fraction changes in hydrogen from 0.11 to 0.26 and a decrease in methane from 0.05 to 0.01 as the temperature rose from 550 °C to 750 °C.

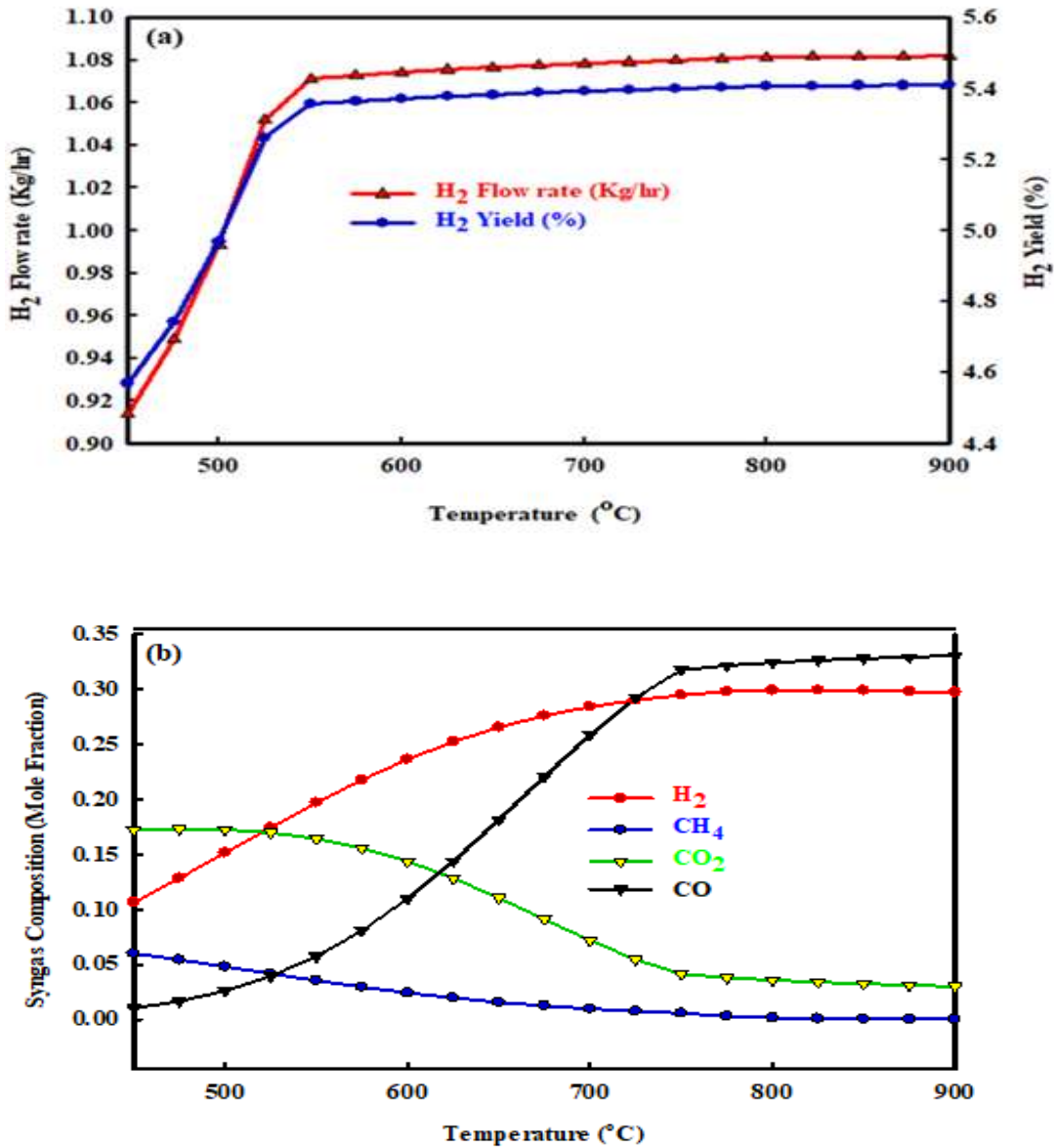


Figure 4-9: Influence of Temperature on (a) hydrogen flow rate and yield, (b) Syngas Composition

Further increase in temperature from 750 °C to 900 °C resulted in a small increase in mole fraction of hydrogen but a decrease in methane. This could be following Le

Chatelier's principle of endothermic ($\text{CO} + 3\text{H}_2 \rightleftharpoons \text{CH}_4 + \text{H}_2\text{O}$) reaction products being favored by higher temperatures with methane reducing probably due to its nature of reaction being exothermic (Mianowski et al., 2024). All components tend to stabilize at 900 °C as the gasification reaction completes. This trend was compared with Diallo et al. (2021) and Puig-Gamero et al. (2018) and found to be similar.

4.2.3 Influence of air-to-fuel ratio

Figure 4-10 illustrates the influence of A/F on the hydrogen flow rate, yield, and syngas composition. The A/F is the proportion of the mass of air to the mass of fuel (biomass) introduced into the gasifier (Samprón et al., 2020). As the A/F increased from 0 to 0.55, the hydrogen flow rate mildly increased from 1.37 to 1.38 kg/hr and yield from 4.58 to 4.59% as observed in Figure 4-10 (a). This may be due to the endothermic gasification reactions. Further increase in A/F from 0.55 to 2.5 escalated oxygen in the reactor, leading to excessive combustion, reducing the hydrogen flow rate and yield to 0.5 Kg/hr and 4.0%, respectively.

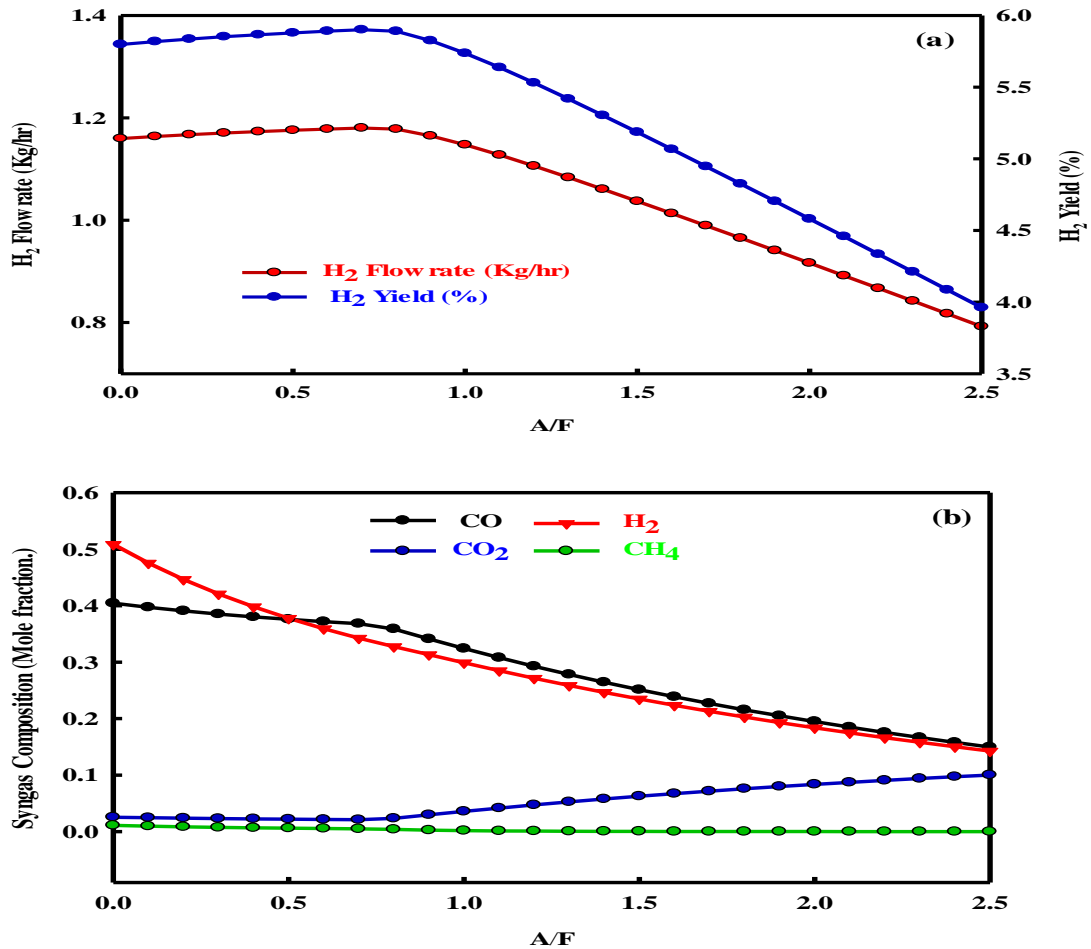


Figure 4-10: Influence of air-to-fuel ratio on (a) hydrogen flow rate, yield, (b) syngas Composition

Excessive combustion increases the production of CO₂ but reduces CO, which is critical in hydrogen formation through the water-gas shift reaction. It is also important to note that an excessive A/F leads to higher temperatures and increased oxidation, which can inhibit water gas shift reactions, lowering the overall hydrogen flow rate and yield in the system.

Figure 4-10 (b) indicates that an increase in A/F from 0.0 to 2.5 caused a general reduction of H₂ and CO from mole fractions of 0.5 to 0.2 and 0.4 to 0.2, respectively. This implies that additional oxygen reacted to reduce H₂, CO, and CH₄ mole fractions but favored CO₂, which increased from 0.01 to 0.1. This could have been due to a stoichiometric reaction where H₂ converted into steam (H₂O) while CO converted into CO₂. A similar tendency was observed by Safarian et al. (2022).

4.2.4 Influence of steam-to-biomass ratio

Figure 4-11 illustrates the effect of SBR on the hydrogen flow rate, yield, and syngas composition.

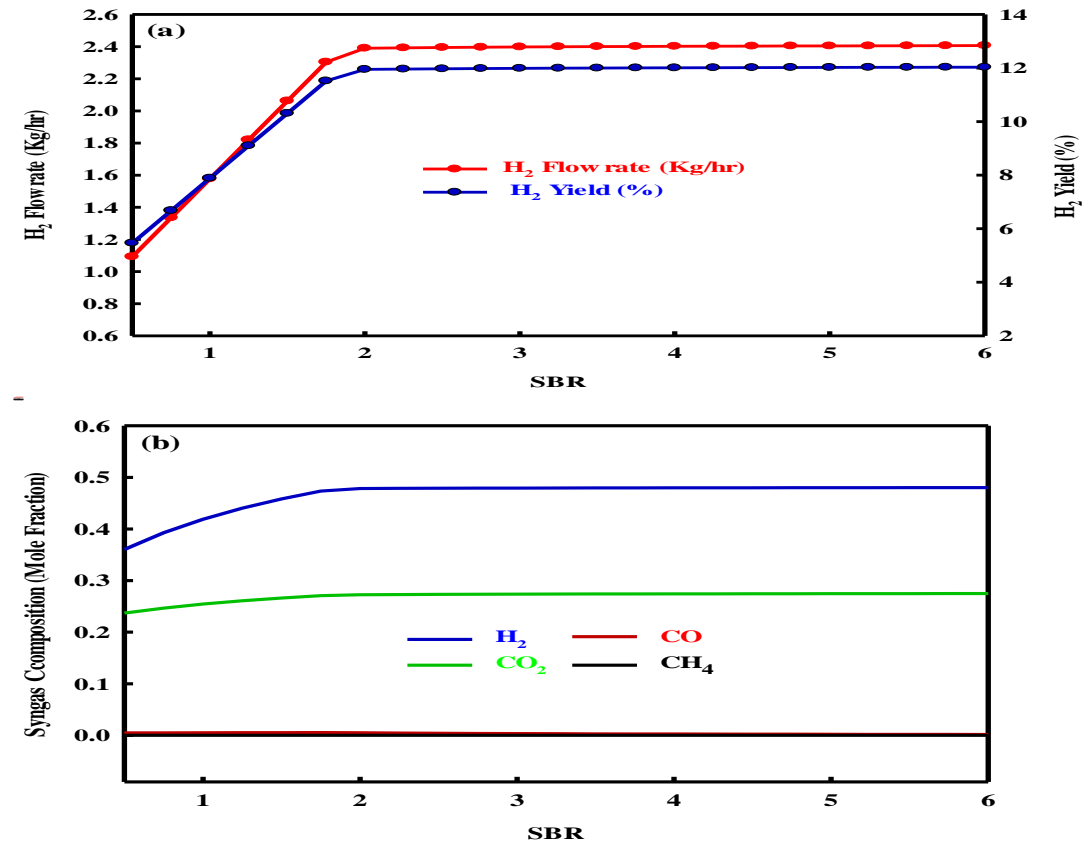


Figure 4-11: Influence of Steam to Biomass ratio on (a) hydrogen flow rate, yield and (b) Syngas Composition

It is evident in Figure 4-11 (a) that an increase in SBR favored hydrogen flow rate and yield to a maximum of 2.4 kg/hr and 12%, and a minimum of 0.8 kg/hr and 1.0%, respectively. It is also observed that as the ratio increased from 0.28 to 6.5, the hydrogen flow rate and yield increased from 0.93 kg/hr. to 2.20 kg/hr. and 3.6% to 12% respectively.

SBR strongly influences the overall hydrogen gas yield in any gasification process. An increase in SBR resulted in a notable increase in hydrogen generation simply because steam (H₂O) reacts with biomass to produce H₂, CO, CH₄, and traces of other gases. Steam reforming and the water-gas shift reactions produce hydrogen since steam reacts with carbon (from the biomass) to form hydrogen and carbon monoxide ($C + H_2O \rightleftharpoons$

CO+H₂). At the same time, there is a shift in equilibrium towards hydrogen production where steam reacts with carbon monoxide to give carbon dioxide and hydrogen gases (CO + H₂O ⇌ CO₂ + H₂) (Brito et al., 2023). A similar trend of hydrogen yield increasing at higher SBR was observed by Hussain et al. (2017).

Figure 4-11 (b) indicates that an increase in SBR caused a decrease in the mole fraction of CO₂, CO, and H₂, weakening their concentration. Despite this, a weak effect of SBR on hydrogen and methane concentrations is observed. Decreases in CO₂ and CO, as well as a low fraction of CH₄ and H₂ in the syngas composition, could have been caused by improved steam methane reforming reactions as SBR increased leading to more steam and/or water in the reaction. This weak effect is also reported by Pala et al., (2017).

4.3 Optimization using Response Surface Methodology (RSM).

Response Surface Methodology is a powerful, robust, and reliable tool that improves the efficiency of the model by identifying optimal operating conditions.

4.3.1 Regression Equation in Uncoded Units.

A mathematical relationship between Temperature, A/F, and SBR in uncoded units and being independent variables of hydrogen and hydrogen yield as a response was developed by RSM as per the second-order polynomial equation. 4-1 and 4-2 respectively.

$$\begin{aligned} H_2 = & -0.0658 + 0.001609 T - 0.2477 A/F + 0.03551 SBR - 0.000001 T \times T \\ & + 0.04481 A/F \times A/F - 0.01899 SBR \times SBR + 0.000003 T \times A/F + 0.000075 T \times SBR \\ & + 0.00097 A/F \times SBR \end{aligned} \quad (4-1)$$

Where Hydrogen mole (H₂) is the response while T, A/F and SBR are the predictor variables with regression coefficients, where T Temperature, A/F=Air to fuel ratio and SBR = Steam to biomass Ratio.

$$\begin{aligned} H_2 \text{ Yield (\%)} = & -31.76 + 0.08451 T + 6.30 A/F + 2.141 SBR - 0.000052 T \times T \\ & - 0.746 A/F \times A/F - 1.2083 SBR \times SBR - 0.005380 T \times A/F + 0.005846 T \times SBR - \\ & 0.520 A/F \times SBR \end{aligned} \quad (4-2)$$

Where Hydrogen yield is the response while T, A/F, and SBR are the predictor variables with regression coefficients, where T= Temperature (°C), A/F=Air to fuel ratio, and SBR = Steam to biomass Ratio

4.3.2 Linear effect of process variables

Figure 4-12 illustrates the direct effect of process variables coded A, B, and C representing temperature, air-to-fuel ratio (A/F), and steam-to-biomass ratio (SBR) respectively, together with their interactions on the response variable being hydrogen mole and yield.

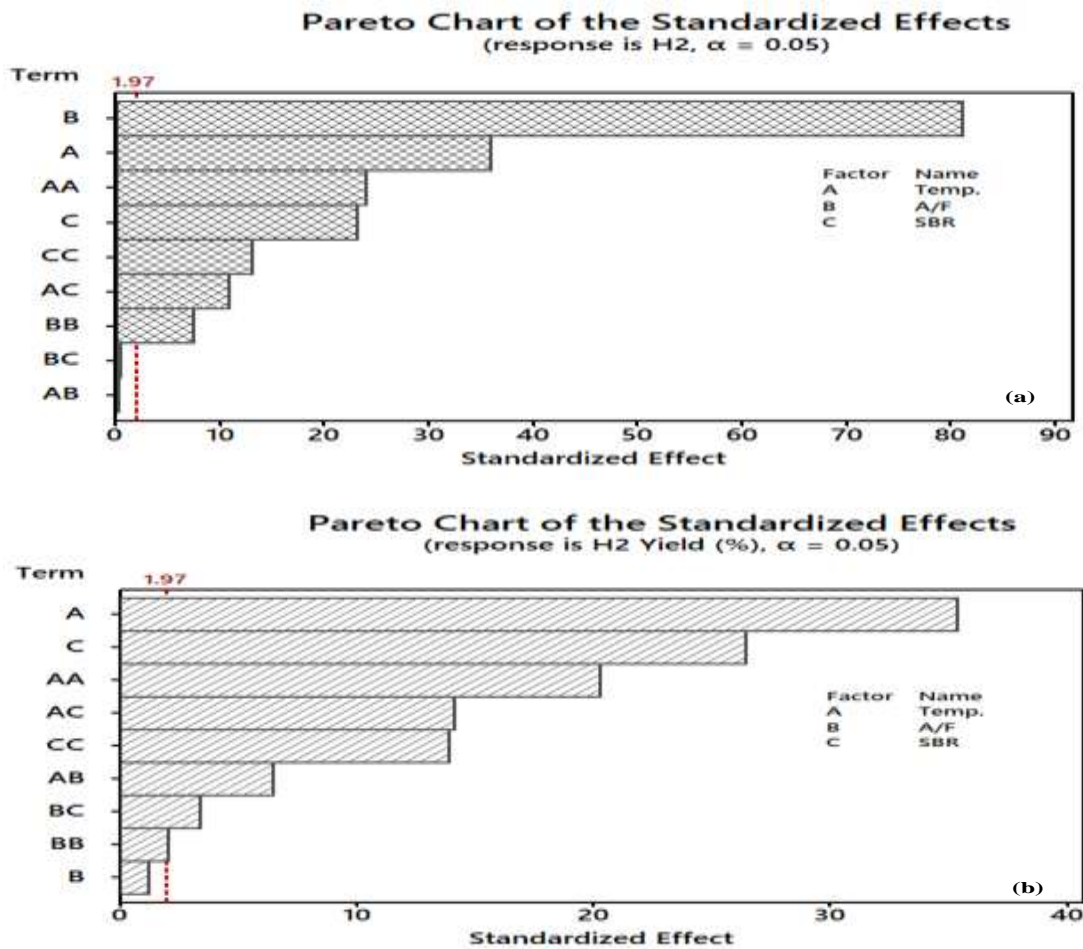


Figure 4-12: Pareto Chart with a standardized effect

It can be observed that A/F had the highest impact in the generation of hydrogen with a standardize effect of 79 while SBR had the lowest with a standardized effect of less than 25. The second-order polynomial equation and the maximum effect of one variable on the model have been found by numerous researchers to best fit the data (Babatabar &

Saidi, 2021; Broer & Brown, 2015; Hussain et al., 2017; Oliveira et al., 2021; Ramos et al., 2019).

4.3.3 Analysis of Variance and Model Summary

Table 4-3 indicates lower p-values of less than 0.0001 for both hydrogen mole fraction and yield, and F-values above 0.04, confirming the models' fitness and significance. This is evident because the significant terms of the model are indicated by P-values less than 0.005 and a higher F-value (Inayat et al., 2020).

Mostly, the terms of this model were found significant for hydrogen yield, apart from Temp. (°C) x A/F and A/F x SBR, which gave warnings as their values were 0.844 and 0.702, for hydrogen mole fraction and A/F of 0.216 for hydrogen yield, respectively. The model summary results in Table 4-3 highlight the R^2 value at 0.9797, signifying that the predicted data of the model approaches the response data. The $Adj.R^2$ value is closer to the R^2 values, and the maximum adjusted ($Adj. R^2$) and predicted R^2 ($Pred.$) values are 0.99788 to 0.9773, respectively. These ANOVA results indicate a reasonable agreement between simulated data and model-anticipated data. A similar trend was observed in the literature (Diallo et al., 2021; Faraji & Saidi, 2022; Puig-Gamero et al., 2018).

Table 4-3: ANOVA and Model Summary results

Analysis of variance											
Hydrogen (mole fraction)						Hydrogen yield (%)					
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.940170	0.104463	1156.49	0.000	Model	9	1014.71	112.745	353.18	0.000
Linear	3	0.758216	0.252739	2798.00	0.000	Linear	3	618.12	206.041	645.44	0.000
Temp.	1	0.116282	0.116282	1287.32	0.000	Temp.	1	400.70	400.702	1255.23	0.000
A/F	1	0.595105	0.595105	6588.26	0.000	A/F	1	0.49	0.491	1.54	0.216
SBR	1	0.048525	0.048525	537.21	0.000	SBR	1	223.69	223.694	700.74	0.000
Square	3	0.071481	0.023827	263.78	0.000	Square	3	191.93	63.977	200.41	0.000
Temp.xTemp.	1	0.051969	0.051969	575.34	0.000	Temp.xTemp.	1	131.97	131.972	413.41	0.000
A/FxA/F	1	0.004969	0.004969	55.01	0.000	A/FxA/F	1	1.38	1.378	4.32	0.039
SBRxSBR	1	0.015261	0.015261	168.95	0.000	SBRxSBR	1	61.79	61.791	193.57	0.000
2-Way	3	0.010553	0.003518	38.94	0.000	2-Way	3	81.63	27.211	85.24	0.000
Interaction						Interaction					
Temp.xA/F	1	0.000004	0.000004	0.04	0.844	Temp.xA/F	1	13.57	13.565	42.50	0.000
Temp.xSBR	1	0.010537	0.010537	116.65	0.000	Temp.xSBR	1	64.26	64.258	201.29	0.000
A/FxSBR	1	0.000013	0.000013	0.15	0.702	A/FxSBR	1	3.81	3.809	11.93	0.001
Error	216	0.019511	0.000090			Error	216	68.95	0.319		
Total	225	0.959681				Total	225	1083.66			
Model Summary											
R²	0.9797					R²	0.9364				
R² (adj)	0.9788					R² (adj)	0.9337				
R² (pred)	0.9773					R² (pred)	0.9296				

4.3.4 Decision variables' effect on Hydrogen mole fraction yield

Figure 4-13 shows the fitted means of the effect of the studied variables on hydrogen yield. It is deduced that as temperature increases from 550 °C to 750 °C, the mole fraction increases from 0.35 to 0.455, and yield increases from 5.5% to 6.4%. The maximum yield is observed at 750 °C, beyond which the yield decreases. This is due to the maximum occurrence of endothermic reactions.

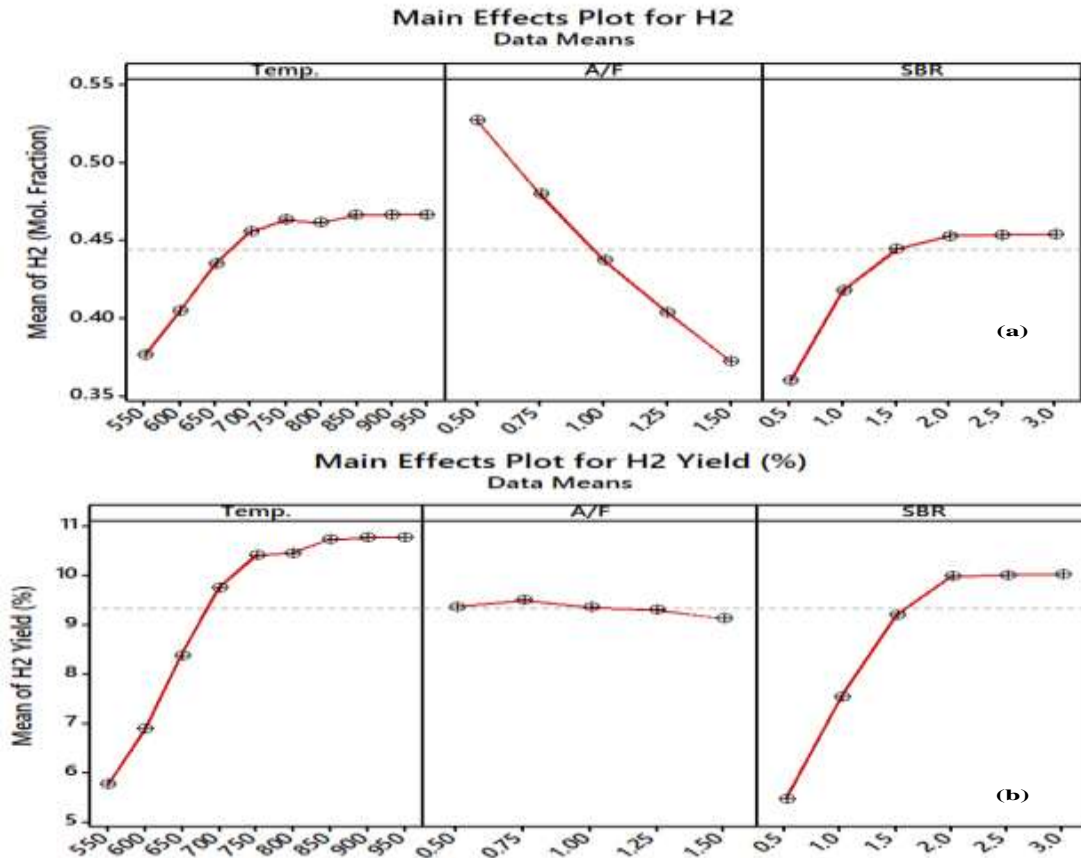


Figure 4-13: Effect of variables on Hydrogen yield

On the other hand, A/F registered a minimal effect on the hydrogen yield as depicted by the negligible ascending yield curve as A/F increases from 0.6 to 1.8. A similar observation was made by Bai et al., 2019. An increase in SBR from 0.28 favoured hydrogen yield as it changed from 4.2% to 7.8%. The impact of these variables is important in making reliable decision with respect to the model on which one had a high effect on the response (Mojaver et al., 2019)

4.3.5 Interrelationship of variables on hydrogen mole fraction and yield

4.3.5.1 Mole fraction

Figure 4-14 (a-b) shows the blended effect of temperature and SBR on the hydrogen mole fraction at a constant A/F of 1.15. It can be observed that the optimal region ranges from a temperature of 750 °C to 950 °C and SBR of 2.0 to 3.0. This gives a corresponding optimal hydrogen mole fraction of 0.45

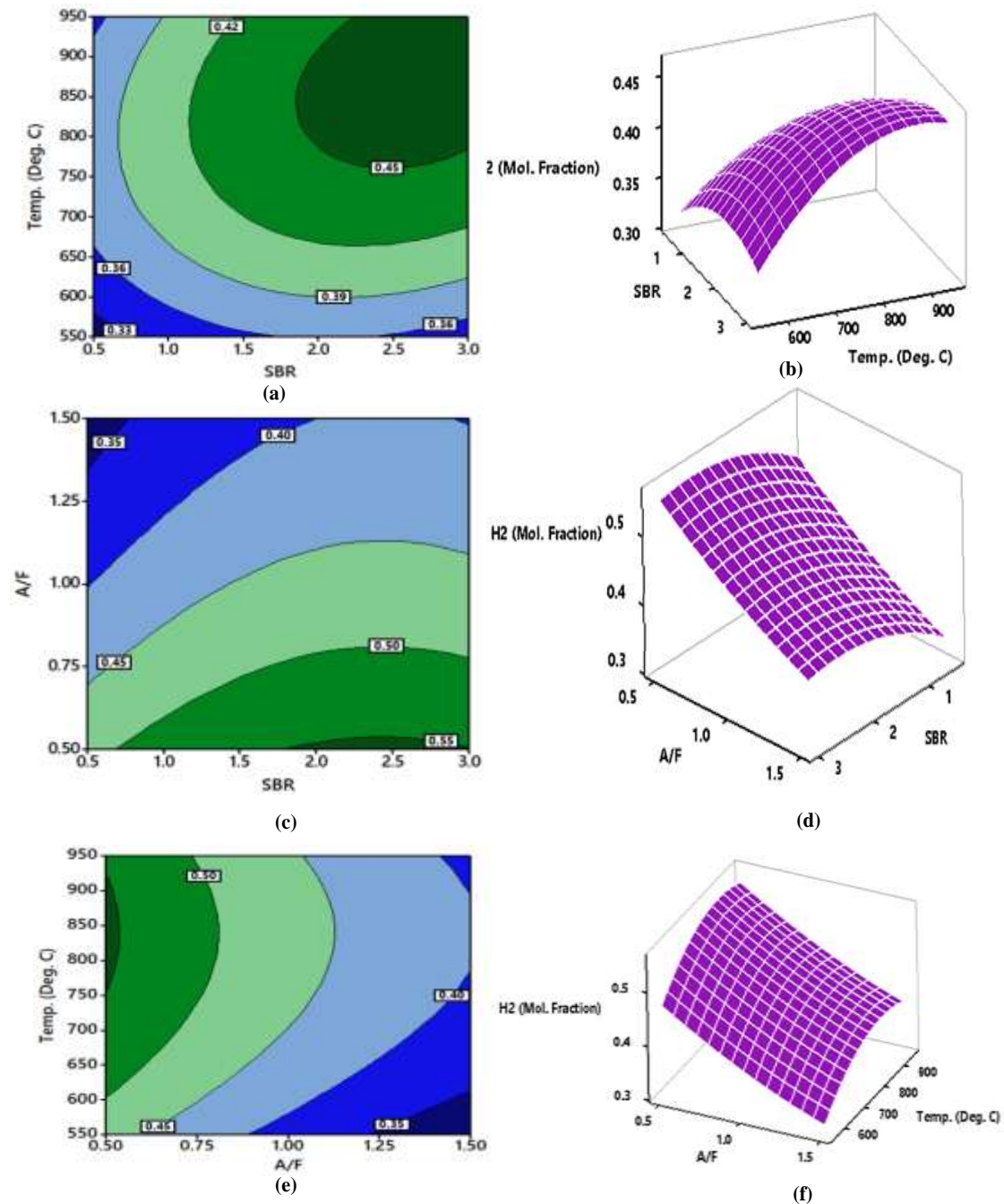


Figure 4-14: Contour and surface plots of the system holding (a-b) A/F at 1.15 (c-d) temperature at 750 °C, and (e-f) SBR at 1.75

Figure 4-14 (c-d) shows the interaction effect of A/F and SBR on hydrogen mole fraction when the temperature is kept constant at 750 °C. It can be observed that an optimal hydrogen mole fraction above 5.5 is attained in the region of low A/F (0.5) and SBR (2.5). Temperature is a significant factor affecting the process yield at every gasification stage. As temperature increases to supercritical conditions (above 550 °C), steam reforming and water gas shift reactions are enhanced, facilitating high hydrogen mole fractions. The enhancement shifts the symmetry of these reactions towards the hydrogen generation as observed by Inayat et al., (2020).

Figure 4-14 (e-f) shows the effect of varying temperature and A/F on hydrogen mole fraction when SBR is kept constant at 1.75. The hydrogen mole fraction is optimized at the high-temperature region of 900 to 950 °C and A/F of 0.5. Increasing temperature enhances the water-gas shift and steam methane reactions improving the hydrogen mole fraction.

4.3.5.2 Hydrogen Yield

Figure 4-15 (a-b) shows the blended effect of temperature and SBR on the hydrogen yield at a constant A/F of 1.15. It can be observed that the optimal region ranges from a temperature of 800 °C to 950 °C and an SBR of 2.5 to 3.0. This gives a corresponding optimal hydrogen yield of 12%.

Figure 4-15 (c-d) shows the interaction effect of A/F and SBR on hydrogen yield when the temperature is kept constant at 750 °C. It can be observed that an optimal hydrogen yield above 11.0% is attained in the region of A/F (1.25) and high SBR (2.5). Temperature is a very critical factor affecting the process yield at every gasification stage. As temperature increases to supercritical conditions (above 550 °C), steam reforming and water-gas shift reactions are enhanced facilitating high hydrogen yields. The enhancement shifts the symmetry of these reactions towards the hydrogen generation as observed by Inayat et al., (2020).

Figure 4-15 (e-f) shows the effect of varying temperature and A/F on hydrogen yield when SBR is kept constant at 1.75. The hydrogen yield is optimized at the high-temperature region of 800 to 950 °C and A/F (0.5). An increase in temperature enhances the water-gas shift and steam methane reactions, increasing the hydrogen yield.

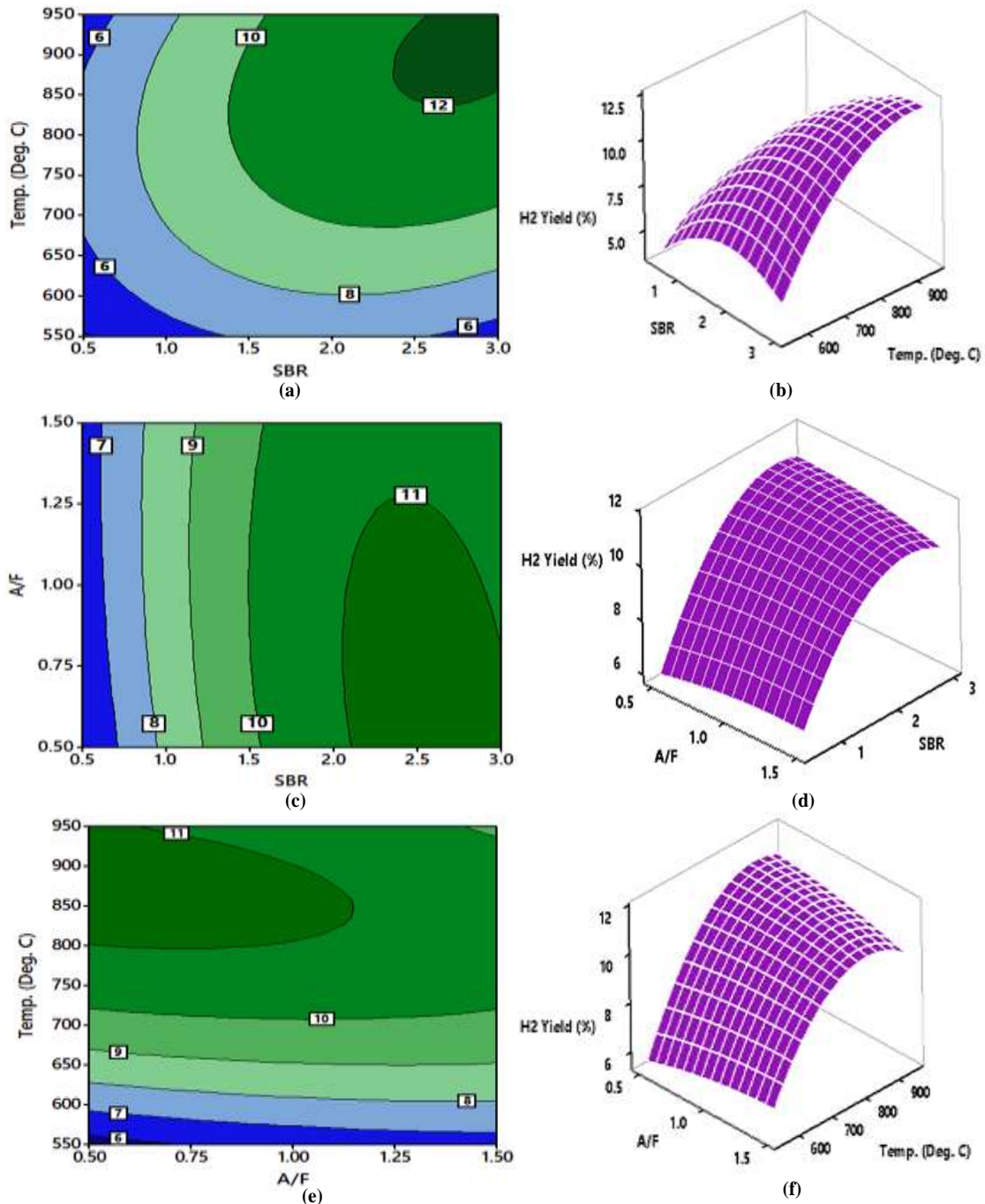


Figure 4-15: Contour and surface plots of the system holding (a-b) A/F at 1.15, (c-d) temperature at 750 °C and (e-f) SBR at 1.75

4.3.6 Parameter Optimization

Parameter optimization in energy conversion studies aims to maximize efficiency, enhance product yield, improve product quality, minimize energy input and reduce emissions and waste. **Error! Reference source not found.** highlights the optimization lot for hydrogen yield generated from RSM. With a desirability of 1, the model setting

depicts effectiveness in achieving favorable response results. The optimal hydrogen yield of 12.994% was observed at a temperature, A/F, and SBR of 889.3939 °C, 0.5, and 2.8737 respectively with a corresponding optimal hydrogen flow rate of 2.5999 Kg/hr.

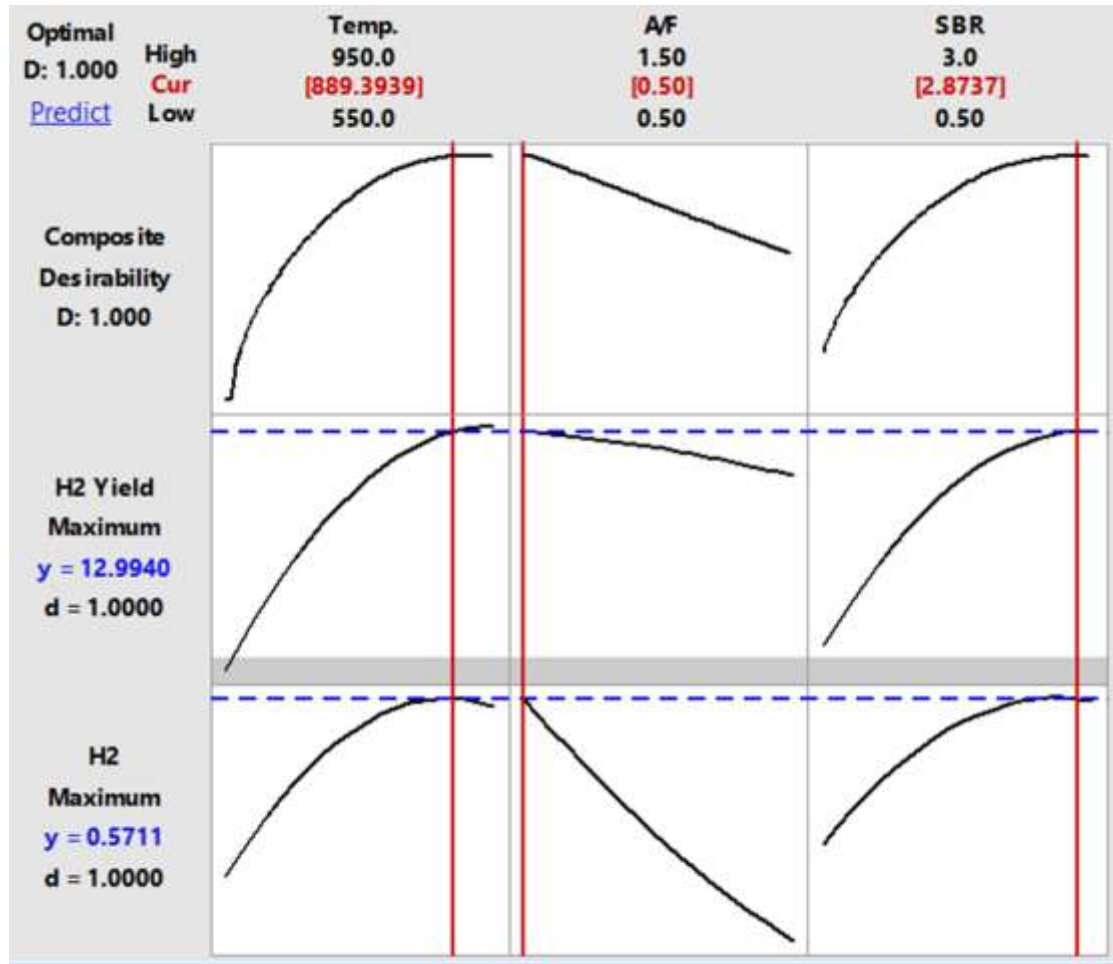


Figure 4-16: Optimal Hydrogen yield at maximum desirability of 1.0

4.4 Findings of Economic Analysis

Using Table 3-3, the total system cost of US \$30,780.425 and 70% plant availability running for 8 hours a day labor agreement (Saravanakumar et al., 2022), with 90% operational, 80% process, and 94.06% gasification efficiencies (Ayub et al., 2023; Murugesan et al., 2022). The total hydrogen generation is $2.5 \text{ kg/hr} \times 8\text{hrs/day} \times 0.7 \times 0.9 \times 0.8 \times 0.94 = 9.4752 \text{ kg/day}$. The energy content of 1 kg hydrogen = 141.9 MJ (HHV) = 39.4 kilowatt-hours (kWh) and 120.1 MJ (LHV) = 33.33 kWh (Tao et al., 2022) Considering hydrogen conversion efficiency of 60% (Handwerker et al., 2021), the system's total energy generated in a month would be $9.4752 \text{ kg/day} \times 33.33 \text{ kWh} \times 0.6 \times$

30 days = 5,684.55 kWh per month. By November 2024, the average cost of electricity price in Kenya was = US \$ 0.2198 per kWh (all taxes inclusive). This translates to a monthly revenue of 5,684.55 kWh x US \$ 0.2198 /kWh = US\$1,249.46. Therefore, the annual revenue collection from the system = US\$1,249.46 x 12 months =US\$14993.6. Assuming two operators earning an average of US \$ 230.77 per month are to be employed, this would translate to an annual labor cost = 2 x US\$230.77 x 12 months = US\$5,538.46. There is a monthly cash outflow increase of US\$384.62 due to system depreciation and maintenance costs. Assuming an 8-year economic lifespan of the plant, with a concession loan at 12%, the NPV, IRR, SPBP, DPBP, and PI are finally computed in Excel software. Table 4.3 highlights the economic analysis results of the project with an NPV of approximately US\$8,741.58, an IRR of 20%, a PBP of 3.6 years, a DPBP of 4.15 years, and a PI of 1.28 after 8 years.

Since a positive NPV implies that an investment is profitable, the study indicates that this project could be highly beneficial as the internal rate of return is 20%. It is also observed that it will only take 3.6 years to repay, and even with the discount rate applied, a period of 4.15 years will be sufficient to realize the project's returns. The project is also very attractive and has a lot of potential, considering the profitability index of 1.28 obtained from this study; hence, it is worthy of investment.

Table 4-3: Economic analysis of the project

Period (years)	Cash inflow	Cash outflow	Net Cash flow	PV¹ (12%)	Undiscounted balance	Discounted balance
0		\$30,780.43	\$-30,780.43	\$-30,780.43	\$ -30,780.43	\$-30,780.43
1	\$14,993.60	\$5,923.08	\$9,070.52	\$8,098.68	\$-21,709.91	\$-22,681.75
2	\$14,993.60	\$6,305.70	\$8,687.90	\$6,925.94	\$-13,022.01	\$-15,755.81
3	\$14,993.60	\$6,688.32	\$8,305.28	\$5,911.53	\$ -4,716.73	\$-9,844.27
4	\$14,993.60	\$7,070.94	\$7,922.66	\$5,034.99	\$3,205.94	\$-4,809.28
5	\$14,993.60	\$7,453.56	\$7,540.04	\$4,278.42	\$10,745.98	\$-530.86
6	\$14,993.60	\$7,836.18	\$7,157.42	\$3,626.17	\$17,903.40	\$3,095.32
7	\$14,993.60	\$8,218.80	\$ 6,774.80	\$3,064.58	\$24,678.20	\$6,159.89
8	\$14,993.60	\$8,601.42	\$ 6,392.18	\$2,581.69	\$1,070.38	\$8,741.58
TOTAL	\$119,948.80	\$88,878.43	\$31,070.38	\$39,522.01	\$17,374.82	\$-66,405.59
NPV ²	\$8,741.58		SPBP ³	3.6 years		
IRR ⁴	20%		DPBP ⁵	4.15 years		
			PI ⁶	1.28		

¹ Present value (PV)

² Net present Value (NPV)

³ Simple Payback period (SPBP)

⁴ Internal Rate of Return (IRR)

⁵ Discounted payback period (DPBP)

⁶ Profitability index (PI)

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study developed a simulation model to generate hydrogen from the air-gasification of food waste from the hotel Industry. The model was integrated with RSM and successfully validated with the experimental and simulated data from previous studies. The study demonstrated the feasibility of biohydrogen from food waste, optimum conditions were identified, and maximum yield was achieved.

Characterization results showed the presence of numerous elements in food wastes, which could vary with changes in sample composition. Due to the heterogeneous nature of food waste and statistically significant differences in sample means, different contents of various parameters were obtained from the five samples containing various types of food waste. Food waste from hotels in Nairobi City County can be used for hydrogen production, owing to the high percentage of total and volatile solids at 93.7% and 84.3%, respectively. However, the presence of crude proteins (22.2%) and lipids (12.1%) in these wastes exhibits the gasification process efficiency. The presence of ash (4.2%) and fixed carbon (11.8%), as well as potassium, sodium, calcium, and phosphorus in their small percentages (0.6%, 1.2%, 0.2%, and 0.4%), respectively, shows the potential of using food wastes in biohydrogen production.

Temperature, A/F, and SBR were investigated. High temperature (889.4 °C and above), A/F (0.5), as well as SBR (2.8737), favored the hydrogen flow rate, yield, and syngas mole fraction. Following RSM analysis, the optimum operating temperature, A/F, and SBR were observed to be from 800 °C - 950 °C, 0.5-0.6, and 2.8, respectively. The modeled updraft moving bed gasification technology offers a promising future through a payback period of 3.6 years. Since NPV of USD 8,741.58, IRR (20%), DPBP (4.15 years), and PI (1.28) were achieved, indicating that the model is viable, these economic results may vary significantly due to the advancement of technologies and changing local economies. The accuracy of the proposed model could be enhanced by incorporating hydrogen storage and hydrodynamics in the future.

5.2 Recommendations

1. The raw syngas produced could be cleaned up by running through the cleaning chamber that separates various components and harmful impurities like mercury, sulfur, and unconverted carbon.
2. Researchers can use this study to measure the carbon footprint of hotels because it is now possible to pull out Carbon dioxide and either store it underground or use it for methanol or ammonia production.
3. Hotels can embrace waste-to-energy technologies and zero-waste systems to save on energy costs and avoid environmental pollution.
4. Research on integrated biohydrogen production technologies using different wastes can be commercially explored for the hotel industry.
5. There is potential for improvement of the model accuracy by incorporating the hydrogen storage and hydrodynamics in future developments

REFERENCES

- Abd, A. A., Othman, M. R., Majdi, H. S., & Helwani, Z. (2023). Green route for biomethane and hydrogen production via integration of biogas upgrading using pressure swing adsorption and steam-methane reforming process. *Renewable Energy*, *210*, 64–78. <https://doi.org/https://doi.org/10.1016/j.renene.2023.04.041>
- Abdalla, A. M., Hossain, S., Nisfindy, O. B., Azad, A. T., Dawood, M., & Azad, A. K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy Conversion and Management*, *165*, 602–627.
- Abdelaal, A. H., McKay, G., & Mackey, H. R. (2019). Food waste from a university campus in the Middle East: Drivers, composition, and resource recovery potential. *Waste Management*, *98*, 14–20. <https://doi.org/10.1016/j.wasman.2019.08.007>
- Abdelhady, S. (2021). Performance and cost evaluation of solar dish power plant: sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV). *Renewable Energy*, *168*, 332–342. <https://doi.org/https://doi.org/10.1016/j.renene.2020.12.074>
- Aboelela, D., Saleh, H., Attia, A. M., Elhenawy, Y., Majozi, T., & Bassyouni, M. (2023). Recent advances in biomass pyrolysis processes for bioenergy production: optimization of operating conditions. *Sustainability*, *15*(14), 11238.
- Acevedo-Paez, J. C., Arenas-Castiblanco, E., Posso, F., Alarcón, E., Villa, A. L., Jahromi, H., & Adhikari, S. (2024). Effect of calcium and potassium on activity of mordenite-supported nickel catalyst for hydrogen production from biomass gasification. *International Journal of Hydrogen Energy*, *52*, 1248–1262.
- Adeleke, A. A., Adedigba, A., Adeshina, S. A., Ikubanni, P. P., Lawal, M. S., Olosho, A. I., Yakubu, H. S., Ogedengbe, T. S., Nzerem, P., & Okolie, J. A. (2024). Comparative studies of machine learning models for predicting higher heating values of biomass. *Digital Chemical Engineering*, *12*, 100159.
- Ahmed, M. W., Esquerre, C. A., Eilts, K., Allen, D. P., McCoy, S. M., Varela, S., Singh, V., Leakey, A. D. B., & Kamruzzaman, M. (2024). Rapid and high-throughput

determination of sorghum (*Sorghum bicolor*) biomass composition using near infrared spectroscopy and chemometrics. *Biomass and Bioenergy*, 186, 107276.

Ahmed, S. F., Mofijur, M., Nuzhat, S., Rafa, N., Musharrat, A., Lam, S. S., & Boretti, A. (2022). Sustainable hydrogen production: Technological advancements and economic analysis. *International Journal of Hydrogen Energy*, 47(88), 37227–37255. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2021.12.029>

Akhlaghi, N., & Najafpour-Darzi, G. (2020). A comprehensive review on biological hydrogen production. *International Journal of Hydrogen Energy*, 45(43), 22492–22512. <https://doi.org/10.1016/J.IJHYDENE.2020.06.182>

Alavi-Borazjani, S. A., Tarelho, L. A. da C., & Capela, M. I. (2021). Parametric optimization of the dark fermentation process for enhanced biohydrogen production from the organic fraction of municipal solid waste using Taguchi method. *International Journal of Hydrogen Energy*, 46(41), 21372–21382. <https://doi.org/10.1016/J.IJHYDENE.2021.04.017>

Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., & Liu, H. (2021). Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. *Journal of Cleaner Production*, 320, 128871.

Aydin, E. S., Yucel, O., & Sadikoglu, H. (2018). *Chapter 2.6 - Numerical Investigation of Fixed-Bed Downdraft Woody Biomass Gasification* (I. Dincer, C. O. Colpan, & O. B. T.-E. Kizilkan Energetic and Environmental Dimensions (eds.); pp. 323–339). Academic Press. <https://doi.org/https://doi.org/10.1016/B978-0-12-813734-5.00018-4>

Ayub, Y., Zhou, J., Ren, J., & He, C. (2023). An innovative integration of torrefaction, gasification, and solid oxide fuel cell for carbon-neutral utilization of biomass waste: Process development, economic, exergy, advanced exergy, and exergoeconomics analysis. *Energy Conversion and Management*, 292, 117426.

Babatabar, M. A., & Saidi, M. (2021). Hydrogen production via integrated configuration of steam gasification process of biomass and water-gas shift reaction: Process simulation and optimization. *International Journal of Energy Research*, 45(13),

19378–19394. <https://doi.org/10.1002/er.7087>

- Bai, B., Liu, Y., Wang, Q., Zou, J., Zhang, H., Jin, H., & Li, X. (2019). Experimental investigation on gasification characteristics of plastic wastes in supercritical water. *Renewable Energy*, *135*, 32–40.
- Barot, S. (2022). Biomass and bioenergy: resources, conversion and application. *Renewable Energy for Sustainable Growth Assessment*, 243–262.
- Bayuo, J., Abukari, M. A., & Pelig-Ba, K. B. (2020). Optimization using central composite design (CCD) of response surface methodology (RSM) for biosorption of hexavalent chromium from aqueous media. *Applied Water Science*, *10*(6), 135. <https://doi.org/10.1007/s13201-020-01213-3>
- Bisht, A. S., & Thakur, N. S. (2019). Small scale biomass gasification plants for electricity generation in India: Resources, installation, technical aspects, sustainability criteria & policy. *Renewable Energy Focus*, *28*, 112–126. <https://doi.org/https://doi.org/10.1016/j.ref.2018.12.004>
- Boni, J., Aida, S., & Leila, K. (2018). Lipid Extraction method from microalgae *botryococcus braunii* as raw material to make biodiesel with soxhlet extraction. *Journal of Physics: Conference Series*, *1095*(1), 12004.
- Bouchareb, E. M., Kerroum, D., Bezirhan Arikan, E., Isik, Z., & Dizge, N. (2021). Production of bio-hydrogen from bulgur processing industry wastewater. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–14.
- Brito, J., Pinto, F., Ferreira, A., Soria, M. A., & Madeira, L. M. (2023). Steam reforming of biomass gasification gas for hydrogen production: from thermodynamic analysis to experimental validation. *Fuel Processing Technology*, *250*, 107859.
- Broer, K. M., & Brown, R. C. (2015). The role of char and tar in determining the gas-phase partitioning of nitrogen during biomass gasification. *Applied Energy*, *158*, 474–483. <https://doi.org/https://doi.org/10.1016/j.apenergy.2015.08.100>
- Cabanlit, J. E. A., & Cruz, K. D. Dela. (2023). Root mean square error of the maximum likelihood estimate of the parameters of pareto distribution. *International Journal*

- Cakar, B., Aydin, S., Varank, G., & Ozcan, H. K. (2020). Assessment of environmental impact of FOOD waste in Turkey. *Journal of Cleaner Production*, 244, 118846.
- Cao, L., Iris, K. M., Xiong, X., Tsang, D. C. W., Zhang, S., Clark, J. H., Hu, C., Ng, Y. H., Shang, J., & Ok, Y. S. (2020). Biorenewable hydrogen production through biomass gasification: A review and future prospects. *Environmental Research*, 186, 109547.
- Capareda, S. C. (2022). Comprehensive biomass characterization in preparation for conversion. In *Sustainable Biochar for Water and Wastewater Treatment* (pp. 1–37). Elsevier.
- Carmona, O. M., Vederza, A., Morales R, A. D., & Lenis, Y. A. (2024). Steady and transient state behavior of a gasification process under fixed-bed downdraft configuration. *Heliyon*, 10(15), e34781.
<https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e34781>
- Carpio-Aguilar, J. C., Rincón-Moreno, J., & Franco-García, M.-L. (2019). Potential of Carbon Footprint Reduction within Retailers: Food Waste at Walmart in Mexico. In *Sustainable Development Goals and Sustainable Supply Chains in the Post-global Economy* (pp. 225–240). Springer.
- Cascant, M. M., Breil, C., Garrigues, S., de la Guardia, M., Fabiano-Tixier, A. S., & Chemat, F. (2017). A green analytical chemistry approach for lipid extraction: computation methods in the selection of green solvents as alternative to hexane. *Analytical and Bioanalytical Chemistry*, 409, 3527–3539.
- Cerone, N., Zimbardi, F., Contuzzi, L., Baleta, J., Cerinski, D., & Skvorčinskienė, R. (2020). Experimental investigation of syngas composition variation along updraft fixed bed gasifier. *Energy Conversion and Management*, 221, 113116.
- Chavan, S., Yadav, B., Atmakuri, A., Tyagi, R. D., Wong, J. W. C., & Drogui, P. (2022). Bioconversion of organic wastes into value-added products: A review. In *Bioresource Technology* (Vol. 344). <https://doi.org/10.1016/j.biortech.2021.126398>

- Chen, W.-H., & Chen, C.-Y. (2020). Water gas shift reaction for hydrogen production and carbon dioxide capture: A review. *Applied Energy*, 258, 114078.
<https://doi.org/https://doi.org/10.1016/j.apenergy.2019.114078>
- Chen, X., Miao, Z., Chen, Y., Zhuang, J., Lv, J., Jiang, E., & Hu, Z. (2024). Effect of alkali and alkaline earth metals on agglomeration in biomass chemical looping gasification. *Journal of the Energy Institute*, 117, 101815.
- Cortazar, M., Santamaria, L., Lopez, G., Alvarez, J., Zhang, L., Wang, R., Bi, X., & Olazar, M. (2023). A comprehensive review of primary strategies for tar removal in biomass gasification. *Energy Conversion and Management*, 276, 116496.
- Cruz, P. L., Navas-Anguila, Z., Iribarren, D., & Dufour, J. (2018). Exergy analysis of hydrogen production via biogas dry reforming. *International Journal of Hydrogen Energy*, 43(26), 11688–11695.
<https://doi.org/https://doi.org/10.1016/j.ijhydene.2018.02.025>
- Czerski, G., Śpiewak, K., Grzywacz, P., & Wierońska-Wiśniewska, F. (2021). Assessment of the catalytic effect of various biomass ashes on CO₂ gasification of tire char. *Journal of the Energy Institute*, 99, 170–177.
- de Oliveira Filho, P. B., Nascimento, M. L. F., & Pontes, K. V. (2018). Optimal Design of a Dividing Wall Column for The Separation of Aromatic Mixtures using the Response Surface Method. *Computer Aided Chemical Engineering*, 43, 361–366.
<https://doi.org/10.1016/B978-0-444-64235-6.50066-8>
- De Paola, M. G., Mazza, I., Paletta, R., Lopresto, C. G., & Calabrò, V. (2021). Small-scale biodiesel production plants—An overview. *Energies*, 14(7), 1901.
- Diallo, A. D. D., Alkhatib, M. F. R., Alam, M. Z., & Mel, M. (2021). Simulation of biomass and municipal solid waste pellet gasification using Aspen Plus. *IOP Conference Series: Materials Science and Engineering*, 1192(1), 12023.
<https://doi.org/10.1088/1757-899X/1192/1/012023>
- Díaz González, C. A., & Pacheco Sandoval, L. (2020). Sustainability aspects of biomass gasification systems for small power generation. *Renewable and Sustainable*

Energy Reviews, 134, 110180. <https://doi.org/10.1016/j.rser.2020.110180>

- Dilkes-Hoffman, L. S., Lane, J. L., Grant, T., Pratt, S., Lant, P. A., & Laycock, B. (2018). Environmental impact of biodegradable food packaging when considering food waste. *Journal of Cleaner Production*, 180, 325–334.
- do Carmo Stangherlin, I., & De Barcellos, M. D. (2018). Drivers and barriers to food waste reduction. *British Food Journal*.
- Dobrowolski, Z., & Drozdowski, G. (2022). Does the net present value as a financial metric fit investment in green energy security? *Energies*, 15(1), 353.
- Edmunds, C. W., Molina, E. A. R., André, N., Hamilton, C., Park, S., Fasina, O., Adhikari, S., Kelley, S. S., Tumuluru, J. S., Rials, T. G., & Labbé, N. (2018). Blended feedstocks for thermochemical conversion: Biomass characterization and bio-oil production from switchgrass-pine residues blends. *Frontiers in Energy Research*, 6(AUG), 1–16. <https://doi.org/10.3389/fenrg.2018.00079>
- El-Azazy, M., El-Shafie, A. S., Issa, A. A., Al-Sulaiti, M., Al-Yafie, J., Shomar, B., & Al-Saad, K. (2019). Potato Peels as an Adsorbent for Heavy Metals from Aqueous Solutions: Eco-Structuring of a *Green* Adsorbent Operating Plackett–Burman Design. *Journal of Chemistry*, 2019, 4926240. <https://doi.org/10.1155/2019/4926240>
- El-Shafay, A. S., Hegazi, A. A., Zeidan, E. S. B., El-Emam, S. H., & Okasha, F. M. (2020). Experimental and numerical study of sawdust air-gasification. *Alexandria Engineering Journal*, 59(5), 3665–3679.
- El Hage, M., Louka, N., Rezzoug, S.-A., Maugard, T., Sablé, S., Koubaa, M., Debs, E., & Maache-Rezzoug, Z. (2023). Bioethanol production from woody biomass: Recent advances on the effect of pretreatments on the bioconversion process and energy yield aspects. *Energies*, 16(13), 5052.
- Elgazar, Y. G., Khalifeh, H. A., Alkhedher, M., & Ramadan, M. (2024). A review of hydrogen production from food waste through gasification process. *International Journal of Hydrogen Energy*, 67, 959–969.

<https://doi.org/https://doi.org/10.1016/j.ijhydene.2024.03.070>

- Etezadi, R., Zhao, L., & Tsotsis, T. (2023). Syngas from food waste. In *Advances in Synthesis Gas: Methods, Technologies and Applications* (pp. 439–455). Elsevier.
- Faizollahzadeh Ardabili, S., Najafi, B., Shamsirband, S., Minaei Bidgoli, B., Deo, R. C., & Chau, K. (2018). Computational intelligence approach for modeling hydrogen production: A review. *Engineering Applications of Computational Fluid Mechanics*, *12*(1), 438–458.
- Faraji, M., & Saidi, M. (2022). Process simulation and optimization of groundnut shell biomass air gasification for hydrogen-enriched syngas production. *International Journal of Hydrogen Energy*, *47*(28), 13579–13591.
- Fatema, J., Ahmed, T., Islam, M. M., Sakib, M. N., Chowdhury, A. M. S., & Haque, P. (2022). Gasification of kitchen wastes in an updraft fluidized bed gasifier and simulation of the process with Aspen Plus. *Journal of Cleaner Production*, *371*, 133670.
- Filimonau, V., & Sulyok, J. (2021). ‘Bin it and forget it!’: The challenges of food waste management in restaurants of a mid-sized Hungarian city. *Tourism Management Perspectives*, *37*, 100759.
- Frolov, S. M. (2021). Organic waste gasification: A selective review. *Fuels*, *2*(4), 556–650.
- Gálvez-Pérez, A., Martín-Lara, M. A., Calero, M., Pérez, A., Canu, P., & Blázquez, G. (2021). Experimental investigation on the air gasification of olive cake at low temperatures. *Fuel Processing Technology*, *213*, 106703.
<https://doi.org/https://doi.org/10.1016/j.fuproc.2020.106703>
- Gani, A., Zaki, M., Mamat, R., Nizar, M., Rosdi, S. M., Yana, S., & Sarjono, R. E. (2023). Analysis of technological developments and potential of biomass gasification as a viable industrial process: A review. *Case Studies in Chemical and Environmental Engineering*, 100439.
- Gao, J., Su, W., Hou, J., Song, X., Wang, J., Lv, P., Xu, G., & Yu, G. (2024). High-

- temperature corrosion behavior of high chromia refractory by alkali metal sodium with different presence states under gasification conditions. *Energy*, *309*, 133093.
- Gao, Y., Wang, M., Raheem, A., Wang, F., Wei, J., Xu, D., Song, X., Bao, W., Huang, A., & Zhang, S. (2023). Syngas Production from Biomass Gasification: Influences of Feedstock Properties, Reactor Type, and Reaction Parameters. *ACS Omega*.
- García, R., Gil, M. V., Rubiera, F., Chen, D., & Pevida, C. (2021). Renewable hydrogen production from biogas by sorption enhanced steam reforming (SESR): A parametric study. *Energy*, *218*, 119491.
<https://doi.org/https://doi.org/10.1016/j.energy.2020.119491>
- Garrison, R. H., Noreen, E. W., & Brewer, P. C. (2021). *Managerial accounting*. McGraw-Hill.
- Gebremariam, S. N., & Marchetti, J. M. (2018). Economics of biodiesel production: Review. *Energy Conversion and Management*, *168*, 74–84.
<https://doi.org/https://doi.org/10.1016/j.enconman.2018.05.002>
- Ghaleb, A. A. S., Kutty, S. R. M., Salih, G. H. A., Jagaba, A. H., Noor, A., Kumar, V., Almahbashi, N. M. Y., Saeed, A. A. H., & Saleh Al-dhawi, B. N. (2021). Sugarcane bagasse as a co-substrate with oil-refinery biological sludge for biogas production using batch mesophilic anaerobic co-digestion technology: Effect of carbon/nitrogen ratio. *Water*, *13*(5), 590.
- Gill, P. E., Murray, W., & Wright, M. H. (2019). *Practical optimization*. SIAM.
- Giordano, C., Piras, S., Boschini, M., & Falasconi, L. (2018). Are questionnaires a reliable method to measure food waste? A pilot study on Italian households. *British Food Journal*.
- Giri, S. (2021). Integrate solid waste management: A case study of a hotel in Kathmandu, Nepal. *EPRA Int J Multidiscip Res*, *7*(5), 264–268.
- Glass, S., & Zelinka, S. (2021). Moisture relations and physical properties of wood. *Chapter 4 in FPL-GTR-282*, 1–4.

- GLOSOLAN. (2019). Standard operating procedure for soil organic carbon Walkley-Black method. *Food and Agriculture Organization of the United Nations*, 1(20), 27.
- Gómez-Marín, N., & Bridgwater, A. V. (2021). Mapping bioenergy stakeholders: A systematic and scientometric review of capabilities and expertise in bioenergy research in the United Kingdom. *Renewable and Sustainable Energy Reviews*, 137, 110496.
- Graham-Rowe, E., Jessop, D. C., & Sparks, P. (2019). Self-affirmation theory and pro-environmental behaviour: Promoting a reduction in household food waste. *Journal of Environmental Psychology*, 62, 124–132.
- Güleç, F., Pekaslan, D., Williams, O., & Lester, E. (2022). Predictability of higher heating value of biomass feedstocks via proximate and ultimate analyses—A comprehensive study of artificial neural network applications. *Fuel*, 320, 123944.
- Haiping, Y., Wang, D., Li, B., Zeng, Z., Qu, L., Zhang, W., & Chen, H. (2017). Effects of potassium salts loading on calcium oxide on the hydrogen production from pyrolysis-gasification of biomass. *Bioresource Technology*, 249. <https://doi.org/10.1016/j.biortech.2017.10.083>
- Han, L., Zhao, J., Rong, N., Wang, Z., Qi, Z., Shen, Z., Ding, H., & Yu, H. (2024). Energy and exergy analyses of biomass IGCC power plant using calcium looping gasification with in situ CO₂ capture and negative carbon emission. *Biomass Conversion and Biorefinery*, 14(19), 23649–23666.
- Handwerker, M., Wellnitz, J., & Marzbani, H. (2021). Comparison of hydrogen powertrains with the battery powered electric vehicle and investigation of small-scale local hydrogen production using renewable energy. *Hydrogen*, 2(1), 76–100.
- Hartikainen, H., Mogensen, L., Svanes, E., & Franke, U. (2018). Food waste quantification in primary production—the Nordic countries as a case study. *Waste Management*, 71, 502–511.
- Hassan, Q., Hafedh, S. A., Mohammed, H. B., Abdulrahman, I. S., Salman, H. M., & Jaszczur, M. (2024). A review of hydrogen production from bio-energy,

- technologies and assessments. *Energy Harvesting and Systems*, 11(1), 20220117.
- Havilah, P. R., Sharma, A. K., Govindasamy, G., Matsakas, L., & Patel, A. (2022). Biomass gasification in downdraft gasifiers: A technical review on production, up-gradation and application of synthesis gas. *Energies*, 15(11), 3938.
- He, C., Du, Y., Cai, X., Wang, J., Qin, Y., Zhao, Z., Li, H., Vassilev, S. V, & Vassileva, C. G. (2023). In-situ analysis of the sintering behavior of coal ash and a phosphorus-rich biomass ash under gasification condition. *Biomass and Bioenergy*, 168, 106671.
- Hedayati Moghaddam, A., Esfandyari, M., Jafari, D., & Sakhaeinia, H. (2023). Multi-factor optimization of bio-methanol production through gasification process via statistical methodology coupled with genetic algorithm. *Results in Engineering*, 20, 101477. <https://doi.org/https://doi.org/10.1016/j.rineng.2023.101477>
- Heeley, K., Orozco, R. L., Macaskie, L. E., Love, J., & Al-Duri, B. (2024). Supercritical water gasification of microalgal biomass for hydrogen production-A review. *International Journal of Hydrogen Energy*, 49, 310–336.
- Hermans, K., & McLeman, R. (2021). Climate change, drought, land degradation and migration: exploring the linkages. *Current Opinion in Environmental Sustainability*, 50, 236–244.
- Hosseinzadeh-Bandbafha, H., Aghbashlo, M., & Tabatabaei, M. (2021). Life cycle assessment of bioenergy product systems: a critical review. *E-Prime-Advances in Electrical Engineering, Electronics and Energy*, 1, 100015.
- Hu, Y., Ma, X., Yu, Z., Zhang, X., Yue, W., & He, T. (2024). NiO–Ca₉Co₁₂O₂₈ bifunctional phase change catalysts for biomass pyrolysis to hydrogen-rich syngas. *International Journal of Hydrogen Energy*, 72, 412–421.
- Hussain, M., Tufa, L. D., Suzana, Y., Zabiri, H., & Taqvi, S. A. A. (2017). *Aspen Plus® Simulation Studies of Steam Gasification in Fluidized Bed Reactor for Hydrogen Production Using Palm Kernel Shell* (pp. 628–641). https://doi.org/10.1007/978-981-10-6463-0_54

- Hwang, J. G., Choi, M. K., Choi, D. H., & Choi, H. S. (2021). Quality improvement and tar reduction of syngas produced by bio-oil gasification. *Energy*, *236*, 121473.
- Ilham, Z. (2022). *Chapter 3 - Biomass classification and characterization for conversion to biofuels* (S. Yusup & N. A. B. T.-V.-C. of B. Rashidi (eds.); pp. 69–87). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-12-824388-6.00014-2>
- Inayat, A., Ahmad, M. M., Mutalib, M. I. A., Yusup, S., & Khan, Z. (2017). Economic analysis and optimization for bio-hydrogen production from oil palm waste via steam gasification. *Energy Sources, Part B: Economics, Planning, and Policy*, *12*(2), 158–165.
- Inayat, M., Sulaiman, S. A., Shahbaz, M., & Bhayo, B. A. (2020). Application of response surface methodology in catalytic co-gasification of palm wastes for bioenergy conversion using mineral catalysts. *Biomass and Bioenergy*, *132*, 105418.
- Indrawan, N., Simkins, B., Kumar, A., & Huhnke, R. L. (2020). Economics of distributed power generation via gasification of biomass and municipal solid waste. *Energies*, *13*(14), 3703.
- Iurchenkova, A., Kobets, A., Ahaliabadeh, Z., Kosir, J., Laakso, E., Virtanen, T., Siipola, V., Lahtinen, J., & Kallio, T. (2024). The effect of the pyrolysis temperature and biomass type on the biocarbons characteristics. *ChemSusChem*, *17*(8), e202301005.
- Jamal, S., Jamil, D., & Khidhir, Z. (2020). Protein Determination in some Animal Products from Sulaymaniyah Markets Using Kjeldahl Procedure. *Journal of Food and Dairy Sciences*, *11*(12), 343–346. <https://doi.org/10.21608/jfds.2020.160394>
- Javadinejad, S., Dara, R., & Jafary, F. (2021). Analysis and prioritization the effective factors on increasing farmers resilience under climate change and drought. *Agricultural Research*, *10*(3), 497–513.
- Jayah, T. H., Aye, L., Fuller, R. J., & Stewart, D. F. (2003). Computer simulation of a downdraft wood gasifier for tea drying. *Biomass and Bioenergy*, *25*(4), 459–469.
- Jha, S., Okolie, J. A., Nanda, S., & Dalai, A. K. (2022). A review of biomass resources and thermochemical conversion technologies. *Chemical Engineering & Technology*,

45(5), 791–799.

- Jiménez-Ocampo, U. E., Santiago, S. G., Vargas, A., & Moreno-Andrade, I. (2021). Feedback control strategy for optimizing biohydrogen production from organic solid waste in a discontinuous process. *International Journal of Hydrogen Energy*, 46(72), 35831–35839.
- Kalak, T. (2023). Potential use of industrial biomass waste as a sustainable energy source in the future. *Energies*, 16(4), 1783.
- Kamran, M. (2021). Bioenergy. *Renewable Energy Conversion Systems*, 243–264. <https://doi.org/10.1016/B978-0-12-823538-6.00002-6>
- Kamyab, S., Ataei, S. A., Tabatabaee, M., & Mirhosseini, S. A. (2019). Optimization of bio-hydrogen production in dark fermentation using activated sludge and date syrup as inexpensive substrate. *International Journal of Green Energy*, 16(10), 763–769. <https://doi.org/10.1080/15435075.2019.1631828>
- Karoki, W. H., Karanja, D. N., Bebora, L. C., & Njagi, L. W. (2018). Isolation, characterization, and quantification of bacteria from African sausages sold in Nairobi County, Kenya. *International Journal of Food Science*, 2018.
- Kartal, F., Sezer, S., & Özveren, U. (2022). Investigation of steam and CO₂ gasification for biochar using a circulating fluidized bed gasifier model in Aspen HYSYS. *Journal of CO₂ Utilization*, 62, 102078.
- Karthikeyan, O. P., Trably, E., Mehariya, S., Bernet, N., Wong, J. W. C., & Carrere, H. (2018). Pretreatment of food waste for methane and hydrogen recovery: a review. *Bioresource Technology*, 249, 1025–1039.
- Kaur, R., Gera, P., Jha, M. K., & Bhaskar, T. (2019). Chapter 8 - Thermochemical Route for Biohydrogen Production. In A. Pandey, S. V. Mohan, J.-S. Chang, P. C. Hallenbeck, & C. B. T.-B. (Second E. Larroche (Eds.), *Biomass, Biofuels, Biochemicals* (pp. 187–218). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-444-64203-5.00008-3>
- Kazmi, B., Sadiq, T., Taqvi, S. A. A., Nasir, S., Khan, M. M., Naqvi, S. R., &

- AlMohamadi, H. (2024). Towards a sustainable future: Bio-hydrogen production from food waste for clean energy generation. *Process Safety and Environmental Protection*, *183*, 555–567.
- Khairy, M., Amer, M., Ibrahim, M., Ookawara, S., Sekiguchi, H., & Elwardany, A. (2024). The influence of torrefaction on the biochar characteristics produced from sesame stalks and bean husk. *Biomass Conversion and Biorefinery*, *14*(15), 17127–17148.
- Kim, R.-H., Lee, N.-H., Yoon, S.-P., Song, S.-H., & Park, J.-K. (2023). Considerations on the methane correction factor and fraction of methane parameters in the IPCC first-order decay model for active aeration landfills. *Waste Management*, *169*, 232–242.
- Kiran, D. R. (2022). *Chapter Six - Wealth and time value of money* (D. R. B. T.-P. of E. and M. for M. E. Kiran (ed.); pp. 53–72). Butterworth-Heinemann.
<https://doi.org/https://doi.org/10.1016/B978-0-323-99862-8.00003-0>
- Klinghoffer, N. B., Castaldi, M. J., & Nzihou, A. (2015). Influence of char composition and inorganics on catalytic activity of char from biomass gasification. *Fuel*, *157*, 37–47.
- Knutsson, P., Cantatore, V., Seemann, M., Tam, P. L., & Panas, I. (2018). Role of potassium in the enhancement of the catalytic activity of calcium oxide towards tar reduction. *Applied Catalysis B: Environmental*, *229*, 88–95.
<https://doi.org/https://doi.org/10.1016/j.apcatb.2018.02.002>
- Kombe, E. Y., Lang'at, N., Njogu, P., Malessa, R., Weber, C. T., Njoka, F., & Krause, U. (2022). Process modeling and evaluation of optimal operating conditions for production of hydrogen-rich syngas from air gasification of rice husks using aspen plus and response surface methodology. *Bioresource Technology*, *361*(July), 127734. <https://doi.org/10.1016/j.biortech.2022.127734>
- Koshariya, A. K., Krishnan, M. S., Jaisankar, S., Loganathan, G. B., Sathish, T., Ağbulut, Ü., Saravanan, R., & Pham, N. D. K. (2024). Waste to energy: An experimental study on hydrogen production from food waste gasification.

International Journal of Hydrogen Energy, 54, 1–12.

- Kumar, R., Kumar, A., & Pal, A. (2024). Simulation modelling of hydrogen production from steam reforming of methane and biogas. *Fuel*, 362, 130742.
<https://doi.org/https://doi.org/10.1016/j.fuel.2023.130742>
- Kuppam, C., Pandit, S., Kadier, A., Chakradhar, D., & Jeevitha, V. (2017). Biohydrogen Production: Integrated Approaches to Improve the Process Efficiency. In *Microbial Applications* (pp. 189–210). https://doi.org/10.1007/978-3-319-52666-9_9
- Kurian, V., Gill, M., Dhakal, B., & Kumar, A. (2022). *Chapter 21 - Recent trends in the pyrolysis and gasification of lignocellulosic biomass* (B. Gurunathan & R. B. T.-B. and B. Sahadevan (eds.); pp. 511–552). Elsevier.
<https://doi.org/https://doi.org/10.1016/B978-0-323-90040-9.00028-X>
- Lamidi, S., Olaleye, N., Bankole, Y., Obalola, A., Aribike, E., & Adigun, I. (2022). *Applications of response surface methodology (RSM) in product design, development, and process optimization*. IntechOpen.
- Lee, C. S., Conradie, A. V., & Lester, E. (2021). Review of supercritical water gasification with lignocellulosic real biomass as the feedstocks: Process parameters, biomass composition, catalyst development, reactor design and its challenges. *Chemical Engineering Journal*, 415, 128837.
- Leng, L., Yang, L., Chen, J., Leng, S., Li, H., Li, H., Yuan, X., Zhou, W., & Huang, H. (2020). A review on pyrolysis of protein-rich biomass: Nitrogen transformation. *Bioresource Technology*, 315, 123801.
- Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., & Malik, A. (2018). The carbon footprint of global tourism. *Nature Climate Change*, 8(6), 522–528.
- Lestari, R. A. S., Kasmiyatun, M., Purwaningtyas, E. F., Shobib, A., Brito Da Silva, T. M. F., Supriyono, & Teixeira, J. A. (2024). Process variable optimization on hydrogen production from sawdust mill of *Paraserianthes falcataria* wood with one stage gasification process using promoted calcium hydroxide absorption. *Biomass Conversion and Biorefinery*, 1–10.

- Li, H., Wang, Y., Zhou, N., Dai, L., Deng, W., Liu, C., Cheng, Y., Liu, Y., Cobb, K., & Chen, P. (2021). Applications of calcium oxide–based catalysts in biomass pyrolysis/gasification—a review. *Journal of Cleaner Production*, 291, 125826.
- Li, J., Chen, Z., Li, L., Qiao, Y., Yuan, Z., Zeng, L., & Li, Z. (2021). Study on pore and chemical structure characteristics of atmospheric circulating fluidized bed coal gasification fly ash. *Journal of Cleaner Production*, 308, 127395.
- Li, Y., Zhu, T., Ling, Y., Yin, Y., & Nong, G. (2024). Solid waste of calcium lignin replaces fossil fuel power by gasification to reduce CO₂ emissions. *Process Safety and Environmental Protection*, 182, 857–865.
- Li, Z., Chen, Z., Yang, N., Wei, K., Ling, Z., Liu, Q., Chen, G., & Ye, B. H. (2021). Trends in research on the carbon footprint of higher education: A bibliometric analysis (2010–2019). *Journal of Cleaner Production*, 289, 125642.
- Lieber, M., Chin-Hong, P., Kelly, K., Dandu, M., & Weiser, S. D. (2022). A systematic review and meta-analysis assessing the impact of droughts, flooding, and climate variability on malnutrition. *Global Public Health*, 17(1), 68–82.
- Liu, N., Jiang, J., Yan, F., Xu, Y., Yang, M., Gao, Y., Aihemaiti, A., & Zou, Q. (2018). Optimization of simultaneous production of volatile fatty acids and bio-hydrogen from food waste using response surface methodology. *RSC Advances*, 8(19), 10457–10464.
- Liu, S., Li, W., Zheng, G., Yang, H., & Li, L. (2020). Optimization of Cattle Manure and Food Waste Co-Digestion for Biohydrogen Production in a Mesophilic Semi-Continuous Process. *Energies*, 13(15), 3848.
- Liu, W., Liu, A., Qin, H., Yan, Y., Fu, D., & Singh, R. P. (2024). Application of hybrid multi-criteria decision-making approach to analyze wastewater microalgae culture systems for bioenergy production. *Environmental Research*, 256, 119234.
- Liu, W., Tian, Y., Yan, H., Zhou, X., Tan, Y., Yang, Y., Li, Z., & Yuan, L. (2021). Gasification of biomass using oxygen-enriched air as gasification agent: a simulation study. *Biomass Conversion and Biorefinery*, 1–8.

- Lu, C., Zhang, H., Zhang, Q., Tahir, N., Hu, J., He, C., Zhu, S., Xia, C., Tang, G., & Jin, P. (2019). Optimization of biohydrogen production from cornstalk through surface response methodology. *Journal of Biobased Materials and Bioenergy*, *13*(6), 830–839.
- Lubwama, M., Yiga, V. A., Muhairwe, F., & Kihedu, J. (2020). Physical and combustion properties of agricultural residue bio-char bio-composite briquettes as sustainable domestic energy sources. *Renewable Energy*, *148*, 1002–1016.
- Lusimbo, I. R. (2019). *Assessment Of Radiological Hazards Associated With Indoor Norm Dose Exposure In Residential Houses In Nairobi, Kenya*. University of Nairobi.
- Magdalena Ramirez, A. H. (2017). *Bioenergy Technologies Office (BETO) 2017 Project Peer Review Technology Area : Conversion Platform*. 1–25.
- Mahmoodi-Eshkaftaki, M., & Mockaitis, G. (2022). Structural optimization of biohydrogen production: Impact of pretreatments on volatile fatty acids and biogas parameters. *International Journal of Hydrogen Energy*, *47*(11), 7072–7081.
- Mahmudul, H. M., Akbar, D., Rasul, M. G., Narayanan, R., & Mofijur, M. (2022). Estimation of the sustainable production of gaseous biofuels, generation of electricity, and reduction of greenhouse gas emissions using food waste in anaerobic digesters. *Fuel*, *310*. <https://doi.org/10.1016/j.fuel.2021.122346>
- Maitlo, G., Ali, I., Mangi, K. H., Ali, S., Maitlo, H. A., Unar, I. N., & Pirzada, A. M. (2022). Thermochemical conversion of biomass for syngas production: Current status and future trends. *Sustainability*, *14*(5), 2596.
- Mandrile, L., Cagnasso, I., Berta, L., Giovannozzi, A. M., Petrozziello, M., Pellegrino, F., Asproudi, A., Durbiano, F., & Rossi, A. M. (2020). Direct quantification of sulfur dioxide in wine by Surface Enhanced Raman Spectroscopy. *Food Chemistry*, *326*, 127009.
- Mandru, A., Mane, J., & Mandapati, R. (2023). A Review on UV-visible spectroscopy. *Journal of Pharma Insights and Research*, *1*(2), 91–96.

- Manikandan, S., Vickram, S., Sirohi, R., Subbaiya, R., Krishnan, R. Y., Karmegam, N., Sumathijones, C., Rajagopal, R., Chang, S. W., & Ravindran, B. (2023). Critical review of biochemical pathways to transformation of waste and biomass into bioenergy. *Bioresource Technology*, *372*, 128679.
- Mankasem, J., Prasertcharoensuk, P., & Phan, A. N. (2024). Intensification of two-stage biomass gasification for hydrogen production. *International Journal of Hydrogen Energy*, *49*, 189–202.
- Manurung, J. (2019). Application of FIFO algorithm (First In First Out) to simulation queue. *INFOKUM*, *7*(2, Juni), 44–47.
- Marcantonio, V., Monarca, D., Villarini, M., Di Carlo, A., Del Zotto, L., & Bocci, E. (2020). Biomass steam gasification, high-temperature gas cleaning, and SOFC model: a parametric analysis. *Energies*, *13*(22), 5936.
- Martinez-Burgos, W. J., Sydney, E. B., de Paula, D. R., Medeiros, A. B. P., de Carvalho, J. C., Soccol, V. T., de Souza Vandenberghe, L. P., Woiciechowski, A. L., & Soccol, C. R. (2020). Biohydrogen production in cassava processing wastewater using microbial consortia: Process optimization and kinetic analysis of the microbial community. *Bioresource Technology*, *309*, 123331.
<https://doi.org/10.1016/J.BIORTECH.2020.123331>
- Martins, A. H., Rouboa, A., & Monteiro, E. (2023). On the green hydrogen production through gasification processes: A techno-economic approach. *Journal of Cleaner Production*, *383*, 135476.
<https://doi.org/https://doi.org/10.1016/j.jclepro.2022.135476>
- Mathews, O. N. (2019). *Industrial Discharge in Nairobi: An Analysis of Regulatory Environment, Quality of Discharge and Media Coverage*. School of Environmental Studies, Kenyatta University.
- Mauer, L. J. (2024). Moisture and total solids analysis. In *Nielsen's Food Analysis* (pp. 233–260). Springer.
- Mehdi, M., Ammar Taqvi, S. A., Shaikh, A. A., Khan, S., Naqvi, S. R., Shahbaz, M., &

- Juchelková, D. (2023). Aspen plus simulation model of municipal solid waste gasification of metropolitan city for syngas production. *Fuel*, *344*, 128128. <https://doi.org/https://doi.org/10.1016/j.fuel.2023.128128>
- Mianowski, A., Szul, M., Radko, T., Sobolewski, A., & Iluk, T. (2024). Literature Review on Thermodynamic and Kinetic Limitations of Thermal Decomposition of Methane. *Energies*, *17*(19), 5007.
- Míguez, J. L., Porteiro, J., Behrendt, F., Blanco, D., Patiño, D., & Dieguez-Alonso, A. (2021). Review of the use of additives to mitigate operational problems associated with the combustion of biomass with high content in ash-forming species. *Renewable and Sustainable Energy Reviews*, *141*, 110502.
- Mohammadidoust, A., & Omidvar, M. R. (2020). Simulation and modeling of hydrogen production and power from wheat straw biomass at supercritical condition through Aspen Plus and ANN approaches. *Biomass Conversion and Biorefinery*. <https://doi.org/10.1007/s13399-020-00933-5>
- Mojaver, P., Khalilarya, S., & Chitsaz, A. (2019). Multi-objective optimization using response surface methodology and exergy analysis of a novel integrated biomass gasification, solid oxide fuel cell and high-temperature sodium heat pipe system. *Applied Thermal Engineering*, *156*, 627–639.
- Mrosso, R., Mecha, A. C., & Kiplagat, J. (2023). Characterization of kitchen and municipal organic waste for biogas production: Effect of parameters. *Heliyon*, *9*(5), e16360. <https://doi.org/10.1016/j.heliyon.2023.e16360>
- Mu, Q., Aleem, R. D., Liu, C., Elendu, C. C., Cao, C., & Duan, P.-G. (2024). Oxygen blown steam gasification of different kinds of lignocellulosic biomass for the production of hydrogen-rich syngas. *Renewable Energy*, *232*, 121132.
- Mukherjee, A., Maity, A., & Chatterjee, S. (2020). Enabling a gasification and carbon capture economy in India: An integrated techno-economic analysis. *Fuel*, *263*, 116595.
- Murugesan, P., Raja, V., Dutta, S., Moses, J. A., & Anandharamakrishnan, C. (2022).

Food waste valorisation via gasification—A review on emerging concepts, prospects and challenges. *Science of The Total Environment*, 851, 157955.

Nair, R., Jain, C., & Gakkhar, N. (2020). Spectrophotometric Determination of Available Sulphate Content in Soil Samples of Jaipur District. *GRD Journal for Engineering*, 5(6), 5–7. www.grdjournals.com

Nazarpour, M., Taghizadeh-Alisaraei, A., Asghari, A., Abbaszadeh-Mayvan, A., & Tatari, A. (2022). Optimization of biohydrogen production from microalgae by response surface methodology (RSM). *Energy*, 253, 124059. <https://doi.org/https://doi.org/10.1016/j.energy.2022.124059>

Nhuchhen, D. R. (2016). Prediction of carbon, hydrogen, and oxygen compositions of raw and torrefied biomass using proximate analysis. *Fuel*, 180, 348–356.

Nikiema, J., Asamoah, B., Egblewogbe, M. N. Y. H., Akomea-Agyin, J., Cofie, O. O., Hughes, A. F., Gebreyesus, G., Asiedu, K. Z., & Njenga, M. (2022). Impact of material composition and food waste decomposition on characteristics of fuel briquettes. *Resources, Conservation & Recycling Advances*, 15, 200095.

Nouwe Edou, D. J., & Onwudili, J. A. (2022). Comparative techno-economic modelling of large-scale thermochemical biohydrogen production technologies to fuel public buses: A case study of West Midlands region of England. *Renewable Energy*, 189, 704–716. <https://doi.org/https://doi.org/10.1016/j.renene.2022.02.074>

Nunes, L. J. R. (2022). Biomass gasification as an industrial process with effective proof-of-concept: A comprehensive review on technologies, processes and future developments. *Results in Engineering*, 14, 100408.

Okos, M. R., Campanella, O., Narsimhan, G., Singh, R. K., & Weitnauer, A. C. (2018). Food dehydration. In *Handbook of food engineering* (pp. 799–950). CRC Press.

Oliveira, M., Ramos, A., Monteiro, E., & Rouboa, A. (2021). Modeling and simulation of a fixed bed gasification process for thermal treatment of municipal solid waste and agricultural residues. *Energy Reports*, 7, 256–269.

Ong, H. C., Chen, W.-H., Singh, Y., Gan, Y. Y., Chen, C.-Y., & Show, P. L. (2020). A

state-of-the-art review on thermochemical conversion of biomass for biofuel production: A TG-FTIR approach. *Energy Conversion and Management*, 209, 112634.

Pala, L. P. R., Wang, Q., Kolb, G., & Hessel, V. (2017). Steam gasification of biomass with subsequent syngas adjustment using shift reaction for syngas production: An Aspen Plus model. *Renewable Energy*, 101, 484–492.
<https://doi.org/https://doi.org/10.1016/j.renene.2016.08.069>

Park, M.-J., Kim, J.-H., Lee, Y.-H., Kim, H.-M., & Jeong, D.-W. (2020). System optimization for effective hydrogen production via anaerobic digestion and biogas steam reforming. *International Journal of Hydrogen Energy*, 45(55), 30188–30200.
<https://doi.org/https://doi.org/10.1016/j.ijhydene.2020.08.027>

Passos, M. L. C., & Saraiva, M. L. M. F. S. (2019). Detection in UV-visible spectrophotometry: Detectors, detection systems, and detection strategies. *Measurement*, 135, 896–904.

Pathak, A. K., Dhaigude, N. D., Sahu, G., Chauhan, V., Saha, S., Datta, S., Singh, R. K., Sahu, A., & Chavan, P. D. (2023). A Review of Factors Affecting Gasifier Performance. *ChemBioEng Reviews*, 10(5), 779–800.

Pathak, G., & Dudhagi, S. S. (2021). Bioenergy crops as an alternate energy resource. *Bioprospecting of Plant Biodiversity for Industrial Molecules*, 357–376.

Phan, T. S., Minh, D. P., Espitalier, F., Nzihou, A., & Grouset, D. (2022). Hydrogen production from biogas: Process optimization using ASPEN Plus®. *International Journal of Hydrogen Energy*, 47(100), 42027–42039.

Pobirchenko, V., Shutaieva, E., Karlova, A., & Polyukhovich, E. (2019). Territory brand: Approaches to definition, simulation methodology. *Journal of Environmental Management & Tourism*, 10(6 (38)), 1351–1364.

Polag, D., & Keppler, F. (2019). Global methane emissions from the human body: Past, present and future. *Atmospheric Environment*, 214, 116823.

Pour, F. H., & Makkawi, Y. T. (2021). A review of post-consumption food waste

- management and its potentials for biofuel production. *Energy Reports*, 7, 7759–7784.
- Puig-Gamero, M., Argudo-Santamaria, J., Valverde, J. L., Sánchez, P., & Sanchez-Silva, L. (2018). Three integrated process simulation using aspen plus®: Pine gasification, syngas cleaning and methanol synthesis. *Energy Conversion and Management*, 177, 416–427.
- Qian, C., Li, Q., Zhang, Z., Wang, X., Hu, J., & Cao, W. (2020). Prediction of higher heating values of biochar from proximate and ultimate analysis. *Fuel*, 265, 116925.
- Qin, F., Zhang, C., Zeng, G., Huang, D., Tan, X., & Duan, A. (2022). Lignocellulosic biomass carbonization for biochar production and characterization of biochar reactivity. *Renewable and Sustainable Energy Reviews*, 157, 112056.
- Rago, Y. P., Surroop, D., & Mohee, R. (2018). Assessing the potential of biofuel (biochar) production from food wastes through thermal treatment. *Bioresource Technology*, 248. <https://doi.org/10.1016/j.biortech.2017.06.108>
- Rajasekhar Reddy, B., & Vinu, R. (2017). Feedstock characterization for pyrolysis and gasification. In *Coal and Biomass Gasification: Recent Advances and Future Challenges* (pp. 3–36). Springer.
- Ramalingam, S., Rajendiran, B., & Subramiyan, S. (2020). Recent advances in the performance of Co-Current gasification technology: A review. *International Journal of Hydrogen Energy*, 45(1), 230–262. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2019.10.185>
- Ramos, A., Monteiro, E., & Rouboa, A. (2019). Numerical approaches and comprehensive models for gasification process: A review. *Renewable and Sustainable Energy Reviews*, 110(April), 188–206. <https://doi.org/10.1016/j.rser.2019.04.048>
- Ramzan, N., Ashraf, A., Naveed, S., & Malik, A. (2011). Simulation of hybrid biomass gasification using Aspen plus: A comparative performance analysis for food, municipal solid and poultry waste. *Biomass and Bioenergy*, 35(9), 3962–3969.

- Ranjan, N., Yadav, N., Singh, H., Kumar, S., & Mahajani, S. M. (2023). Modelling and simulation of autothermal downdraft co-gasification of biomass and plastic wastes using Aspen Plus. *Energy Conversion and Management*, 297, 117714.
- Rao, B. J. M., & Barman, M. (2023). Thermal gasification of biomass in fluidized bed. *Materials Today: Proceedings*.
- Razon, L. F., Khang, D. S., Tan, R. R., Aviso, K. B., Yu, K. D. S., & Promentilla, M. A. B. (2019). Life-cycle costing: Analysis of biofuel production systems. *Biofuels for a More Sustainable Future: Life Cycle Sustainability Assessment and Multi-Criteria Decision Making*, 227–253. <https://doi.org/10.1016/B978-0-12-815581-3.00008-7>
- Rey, J. R. C., Longo, A., Rijo, B., Pedrero, C. M., Tarelho, L. A. C., Brito, P. S. D., & Nobre, C. (2024). A review of cleaning technologies for biomass-derived syngas. *Fuel*, 377, 132776.
- Rojas-Flores, S. (2022). Generation of electricity from agricultural waste. *Green Energy and Environmental Technology*.
- Roncancio, R., & Gore, J. P. (2021). CO₂ char gasification: A systematic review from 2014 to 2020. *Energy Conversion and Management: X*, 10, 100060.
- Rubinsin, N. J., Karim, N. A., Timmiati, S. N., Lim, K. L., Isahak, W. N. R. W., & Pudukudy, M. (2024). An overview of the enhanced biomass gasification for hydrogen production. *International Journal of Hydrogen Energy*, 49, 1139–1164. <https://doi.org/https://doi.org/10.1016/j.ijhydene.2023.09.043>
- Safarian, S., Ebrahimi Saryazdi, S. M., Unnthorsson, R., & Richter, C. (2021). Modeling of hydrogen production by applying biomass gasification: Artificial neural network modeling approach. *Fermentation*, 7(2), 71.
- Safarian, S., Unnthorsson, R., & Richter, C. (2022). Hydrogen production via biomass gasification: simulation and performance analysis under different gasifying agents. *Biofuels*, 13(6), 717–726. <https://doi.org/10.1080/17597269.2021.1894781>
- Samimi, F., Marzoughi, T., & Rahimpour, M. R. (2020). Energy and exergy analysis and optimization of biomass gasification process for hydrogen production (based on air,

- steam and air/steam gasifying agents). *International Journal of Hydrogen Energy*, 45(58), 33185–33197.
- Samprón, I., de Diego, L. F., García-Labiano, F., Izquierdo, M. T., Abad, A., & Adánez, J. (2020). Biomass Chemical Looping Gasification of pine wood using a synthetic Fe₂O₃/Al₂O₃ oxygen carrier in a continuous unit. *Bioresource Technology*, 316, 123908.
- Saranya, P., Anantharaj, R., Prakash, D. G., & Vichitra, M. (2022). Experimental investigation of performance of bio diesel with different blends in diesel engine. In *Biofuels and Bioenergy* (pp. 553–567). Elsevier.
- Saravanakumar, A., Chen, W.-H., Arunachalam, K. D., Park, Y.-K., & Chyuan Ong, H. (2022). Pilot-scale study on downdraft gasification of municipal solid waste with mass and energy balance analysis. *Fuel*, 315, 123287.
<https://doi.org/https://doi.org/10.1016/j.fuel.2022.123287>
- Sarmah, M. K., Singh, T. P., Kalita, P., & Dewan, A. (2023). Sustainable hydrogen generation and storage—a review. *RSC Advances*, 13(36), 25253–25275.
- Sathish, T., Kumar, I., Kulkarni, M., sathyamurthy, R., Ganesh, R. S., Reddy, P. N. K., Al-Enizi, A. M., Pandit, B., Gupta, M., Shahazad, M., & Yusuf, M. (2024). Sustainable hydrogen production from waste of expired breads through supercritical water gasification. *International Journal of Hydrogen Energy*.
<https://doi.org/https://doi.org/10.1016/j.ijhydene.2024.01.190>
- Saunio, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., & Patra, P. K. (2020). The global methane budget 2000–2017. *Earth System Science Data*, 12(3), 1561–1623.
- Sazali, N. (2020). Emerging technologies by hydrogen: A review. *International Journal of Hydrogen Energy*, 45(38), 18753–18771.
- Schmid, M., Schmidberger, C., & Scheffknecht, G. (2023). Modelling and simulation of fluidized bed steam-oxygen gasification of sewage sludge using thermochemical equilibrium and experimental data. *Fuel*, 341, 127595.

- Seçer, A., Fakı, E., Üzden, Ş. T., & Hasanoğlu, A. (2020). Hydrothermal co-gasification of sorghum biomass and çan lignite in mild conditions: An optimization study for high yield hydrogen production. *International Journal of Hydrogen Energy*, *45*(4), 2668–2680.
- Segneri, V., Ferrasse, J. H., Trinca, A., & Vilardi, G. (2022). An Overview of Waste Gasification and Syngas Upgrading Processes. In *Energies* (Vol. 15, Issue 17, p. 6391). MDPI.
- Sekoai, P. T., Ayeni, A. O., & Daramola, M. O. (2019). Parametric optimization of biohydrogen production from potato waste and scale-up study using immobilized anaerobic mixed sludge. *Waste and Biomass Valorization*, *10*(5), 1177–1189.
- Shahbeig, H., & Nosrati, M. (2020). Pyrolysis of municipal sewage sludge for bioenergy production: Thermo-kinetic studies, evolved gas analysis, and techno-socio-economic assessment. *Renewable and Sustainable Energy Reviews*, *119*, 109567. <https://doi.org/https://doi.org/10.1016/j.rser.2019.109567>
- Sharma, P., Sivaramakrishnaiah, M., Deepanraj, B., Saravanan, R., & Reddy, M. V. (2024). A novel optimization approach for biohydrogen production using algal biomass. *International Journal of Hydrogen Energy*, *52*, 94–103.
- Shen, Y. (2024). Biomass pretreatment for steam gasification toward H₂-rich syngas production—An overview. *International Journal of Hydrogen Energy*, *66*, 90–102.
- Shi, T., Zhou, J., Ren, J., Ayub, Y., Yu, H., Shen, W., Li, Q., & Yang, A. (2023). Co-valorisation of sewage sludge and poultry litter waste for hydrogen production: Gasification process design, sustainability-oriented optimization, and systematic assessment. *Energy*, *272*, 127131. <https://doi.org/https://doi.org/10.1016/j.energy.2023.127131>
- Sinaga, A. S., Sari, M. M., Hutasuhut, A. A., Zahara, S. T., Amanda, A., Fitri, A., & Caesario, M. A. (2023). Comparison of capital budgeting methods: NPV, IRR, PAYBACK PERIOD. *World Journal of Advanced Research and Reviews*, *19*(2), 1078–1081.

- Singh, D. K., & Tirkey, J. V. (2022). Process modelling and thermodynamic performance optimization of biomass air gasification fuelled with waste poultry litter pellet by integrating Aspen plus with RSM. *Biomass and Bioenergy*, *158*, 106370.
- Singh, D., Yadav, S., Bharadwaj, N., & Verma, R. (2020). Low temperature steam gasification to produce hydrogen rich gas from kitchen food waste: Influence of steam flow rate and temperature. *International Journal of Hydrogen Energy*, *45*(41), 20843–20850.
- Singh, P., Singh, R. K., Song, Q.-Q., Li, H.-B., Yang, L.-T., & Li, Y.-R. (2020). Methods for estimation of nitrogen components in plants and microorganisms. *Nitrogen Metabolism in Plants: Methods and Protocols*, 103–112.
- Slopiecka, K., Liberti, F., Massoli, S., Bartocci, P., & Fantozzi, F. (2022). Chemical and physical characterization of food waste to improve its use in anaerobic digestion plants. *Energy Nexus*, *5*, 100049. <https://doi.org/10.1016/J.NEXUS.2022.100049>
- Song, H., Yang, G., Xue, P., Li, Y., Zou, J., Wang, S., Yang, H., & Chen, H. (2022). Recent development of biomass gasification for H₂ rich gas production. *Applications in Energy and Combustion Science*, *10*, 100059. <https://doi.org/https://doi.org/10.1016/j.jaecs.2022.100059>
- Suarez, E., Tobajas, M., Mohedano, A. F., & de la Rubia, M. A. (2022). Energy recovery from food waste and garden and park waste: Anaerobic co-digestion versus hydrothermal treatment and anaerobic co-digestion. *Chemosphere*, *297*, 134223.
- Sultana, N., Hossain, S. M. Z., Aljameel, S. S., Omran, M. E., Razzak, S. A., Haq, B., & Hossain, M. M. (2023). Biohydrogen from food waste: modeling and estimation by machine learning based super learner approach. *International Journal of Hydrogen Energy*, *48*(49), 18586–18600.
- Taipabu, M. I., Viswanathan, K., Wu, W., Hattu, N., & Atabani, A. E. (2022). A critical review of the hydrogen production from biomass-based feedstocks: Challenge, solution, and future prospect. *Process Safety and Environmental Protection*, *164*, 384–407.

- Tang, X., Pu, W., Chen, Q., Liu, R., & Yang, Y. (2024). An experimental investigation on hydrogen generation from in-situ gasification by pyrolysis. *International Journal of Hydrogen Energy*, *49*, 1019–1027.
- Tao, M., Azzolini, J. A., Stechel, E. B., Ayers, K. E., & Valdez, T. I. (2022). Engineering Challenges in Green Hydrogen Production Systems. *Journal of The Electrochemical Society*, *169*(5), 54503.
- Taqvi, S. A. A., Kazmi, B., Naqvi, S. R., Juchelková, D., & Bokhari, A. (2024). State-of-the-art review of biomass gasification: raw to energy generation. *ChemBioEng Reviews*, *11*(4), e202400003.
- Tavakoli, N., & Saidi, M. (2024). Exergy analysis and cold gas efficiency evaluation for hydrogen generation through algae biomass steam gasification coupled with water-gas shift reaction. *International Journal of Hydrogen Energy*, *57*, 500–514.
<https://doi.org/https://doi.org/10.1016/j.ijhydene.2023.11.323>
- Temel, F. A. (2023). Evaluation of the influence of rice husk amendment on compost quality in the composting of sewage sludge. *Bioresource Technology*, *373*, 128748.
- Tezer, Ö., Karabağ, N., Öngen, A., Çolpan, C. Ö., & Ayol, A. (2022). Biomass gasification for sustainable energy production: A review. *International Journal of Hydrogen Energy*, *47*(34), 15419–15433.
- Thomareis, A. S., & Dimitreli, G. (2022). Techniques used for processed cheese characterization. *Processed Cheese Science and Technology: Ingredients, Manufacture, Functionality, Quality, and Regulations*, 295–349.
<https://doi.org/10.1016/B978-0-12-821445-9.00007-8>
- Tonini, D., Albizzati, P. F., & Astrup, T. F. (2018). Environmental impacts of food waste: Learnings and challenges from a case study on UK. *Waste Management*, *76*, 744–766.
- Ulhiza, T. A., Puad, N. I. M., & Azmi, A. S. (2018). Optimization of culture conditions for biohydrogen production from sago wastewater by *Enterobacter aerogenes* using Response Surface Methodology. *International Journal of Hydrogen Energy*, *43*(49),

22148–22158.

- Uslu, S. (2020). Optimization of diesel engine operating parameters fueled with palm oil-diesel blend: Comparative evaluation between response surface methodology (RSM) and artificial neural network (ANN). *Fuel*, 276, 117990.
- Wang, C., Zhu, L., Zhang, M., Han, Z., Jia, X., Bai, D., Duo, W., Bi, X., Abudula, A., & Guan, G. (2022). A two-stage circulated fluidized bed process to minimize tar generation of biomass gasification for fuel gas production. *Applied Energy*, 323, 119639.
- Wang, F., Peng, W., Zeng, X., Sun, D., Cui, G., Han, Z., Wang, C., & Xu, G. (2024). Insight into staged gasification of biomass waste: Essential fundamentals and applications. *Science of The Total Environment*, 175954.
- Wang, J., Singer, S. D., Souto, B. A., Asomaning, J., Ullah, A., Bressler, D. C., & Chen, G. (2022). Current progress in lipid-based biofuels: Feedstocks and production technologies. *Bioresource Technology*, 351, 127020.
<https://doi.org/https://doi.org/10.1016/j.biortech.2022.127020>
- Wang, J., & Yin, Y. (2017). Optimization of hydrogen production process. In *Green Energy and Technology* (Vol. 0, Issue 9789811046742).
https://doi.org/10.1007/978-981-10-4675-9_7
- Wang, J., & Yin, Y. (2019). Progress in microbiology for fermentative hydrogen production from organic wastes. *Critical Reviews in Environmental Science and Technology*, 49(10), 825–865.
- Wang, P., Shen, C., Wang, B., Xu, P., & Shen, L. (2022). Ammonia production from nitrogen-rich biomass gasification: Nitrogen transformation from model amino acids. *Fuel*, 326, 125071.
- Wang, P., Wang, S., Wang, B., Shen, L., & Song, T. (2022). Green production of ammonia from nitrogen-rich biomass pyrolysis: Evolution of fuel-N under H₂-rich atmosphere. *Fuel Processing Technology*, 227, 107126.
- Wang, W., Li, Q., Wang, Q., Zhang, J., & Liu, J. (2022). Tar steam reforming during

biomass gasification: kinetic model and reaction pathway. *Clean Technologies and Environmental Policy*, 1–12.

Wang, X., Chen, Q., Wei, B., Yu, G., Li, H., Chen, X., Liu, H., & Wang, F. (2023).

Volatile potassium transfer behavior in carbon matrix and its effect on char gasification. *Fuel*, 333, 126302.

Wattana, A., Watanawanyoo, P., & Nirukkanaporn, S. (2020). A study on thermal efficiency of downdraft gasifier (swirl air type). *Journal of Current Science and Technology*, 10(2), 203–215.

Wu, C., Tindall, G. W., Fitzgerald, C. L., Thies, M. C., & Roberts, M. E. (2025).

Decoupling the role of lignin, cellulose/hemi-cellulose, and ash on ZnCl₂-activated carbon pore structure. *Materials Advances*, 6(4), 1431–1441.

Wu, R. (2025). Biomass Conversion Technologies: Transforming Organic Matter into Energy and Materials. In *Biomass Based Products*. IntechOpen.

Xie, D., Zhong, Y., Huang, J., Wang, B., Wang, Z., Hu, W., Zhao, C., & Qiao, Y.

(2022). Steam gasification of the raw and torrefied mixed typical food wastes: Effect of interactions on syngas production. *Fuel*, 323, 124354.

<https://doi.org/https://doi.org/10.1016/j.fuel.2022.124354>

Xu, C. (Charles), Liao, B., Pang, S., Nazari, L., Mahmood, N., Tushar, M. S. H. K., Dutta, A., & Ray, M. B. (2018). 1.19 Biomass Energy (I. B. T.-C. E. S. Dincer (ed.); pp. 770–794). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-12-809597-3.00121-8>

Xu, Z., Qi, H., Yao, D., Zhang, J., Zhu, Z., Wang, Y., & Cui, P. (n.d.). Modeling and Comprehensive Analysis for Novel Food Waste Gasification-Based Hydrogen Production Process. Available at SSRN 3916197.

Xu, Z., Qi, H., Yao, D., Zhang, J., Zhu, Z., Wang, Y., & Cui, P. (2022). Modeling and comprehensive analysis of food waste gasification process for hydrogen production. *Energy Conversion and Management*, 258, 1–28.

<https://doi.org/10.1016/j.enconman.2022.115509>

- Yadav, S., Singh, V., Mahata, C., & Das, D. (2021). Optimization for simultaneous enhancement of biobutanol and biohydrogen production. *International Journal of Hydrogen Energy*, 46(5), 3726–3741.
- Yang, J., Han, C., Shao, L., Nie, R., Dong, S., Liu, H., & Ma, L. (2024). Chemical looping gasification of lignite to syngas using phosphogypsum: Overview and prospects. *Journal of Cleaner Production*, 141329.
- Yang, X., Kang, K., Qiu, L., Zhao, L., & Sun, R. (2020). Effects of carbonization conditions on the yield and fixed carbon content of biochar from pruned apple tree branches. *Renewable Energy*, 146, 1691–1699.
- YANG, Z., Shuai, G. U. O., & WANG, X. (2023). Effect of operating conditions on release and transformation of sodium during CFB gasification of Zhundong coal. *Journal of Fuel Chemistry and Technology*, 51(9), 1232–1239.
- Yu, P., Low, M. Y., & Zhou, W. (2018). Design of experiments and regression modelling in food flavour and sensory analysis: A review. *Trends in Food Science & Technology*, 71, 202–215.
- Yu, Z., Wang, Z., Zhong, H., & Cheng, K. (2024). Essential aspects of the CFD software modelling of biomass gasification processes in downdraft reactors. *RSC Advances*, 14(39), 28724–28739.
- Zaman, S. A., Roy, D., & Ghosh, S. (2020). Process modeling and optimization for biomass steam-gasification employing response surface methodology. *Biomass and Bioenergy*, 143(October), 105847. <https://doi.org/10.1016/j.biombioe.2020.105847>
- Zeng, J., Zeng, H., & Wang, Z. (2022). Review on technology of making biofuel from food waste. In *International Journal of Energy Research*. <https://doi.org/10.1002/er.7868>
- Zhan, Y., & Zhu, J. (2024). Response surface methodology and artificial neural network-genetic algorithm for modeling and optimization of bioenergy production from biochar-improved anaerobic digestion. *Applied Energy*, 355, 122336.
- Zhang, Y., Fu, W., Cui, L., Maqsood, T., & Li, B. (2023). Experimental microwave-

assisted air gasification of biomass for syngas production. *Fuel*, 339, 126954.

Zhang, Y., Wan, L., Guan, J., Xiong, Q., Zhang, S., & Jin, X. (2020). A review on biomass gasification: Effect of main parameters on char generation and reaction. *Energy & Fuels*, 34(11), 13438–13455.

Zhao, C., Huang, J., Xie, D., Qiao, Y., & Xu, M. (2024). Thermodynamic and techno-economic analysis of hydrogen production from food waste by torrefaction integrated with steam gasification. *Energy Conversion and Management*, 299, 117826. <https://doi.org/10.1016/j.enconman.2023.117826>

Zhou, T., Zhang, W., Shen, Y., Luo, S., & Ren, D. (2023). Progress in the change of ash melting behavior and slagging characteristics of co-gasification of biomass and coal: A review. *Journal of the Energy Institute*, 101414.

Zong, P., Jiang, Y., Tian, Y., Li, J., Yuan, M., Ji, Y., Chen, M., Li, D., & Qiao, Y. (2020). Pyrolysis behavior and product distributions of biomass six group components: Starch, cellulose, hemicellulose, lignin, protein and oil. *Energy Conversion and Management*, 216, 112777.

Zou, X., Zhai, M., Liu, G., Guo, L., Zhang, Y., & Wang, X. (2024). Microdynamics of biomass steam gasification: A review. *Energy Conversion and Management*, 306, 118274.

APPENDICES

APPENDIX A: Photos taken during Characterization of Food Wastes.



Figure 0-1: 1-4. Food waste collection & sampling, 5. Wet sample homogenized, 6. pH Measurement, 7-8. Oven @105 °C, 9. Muffle furnace 10. Ash weighing



Figure 0-2: 11. Sample weighing, 12. Empty thimble, 13. Thimble + sample, 14. Soxhlet extractor in operation, 15. Flask + Extracted lipid, 16-17 Sample digestion for Nitrogen and protein, 18 Kjeldahl Protein Apparatus, 19. Distillation, 20. Titration



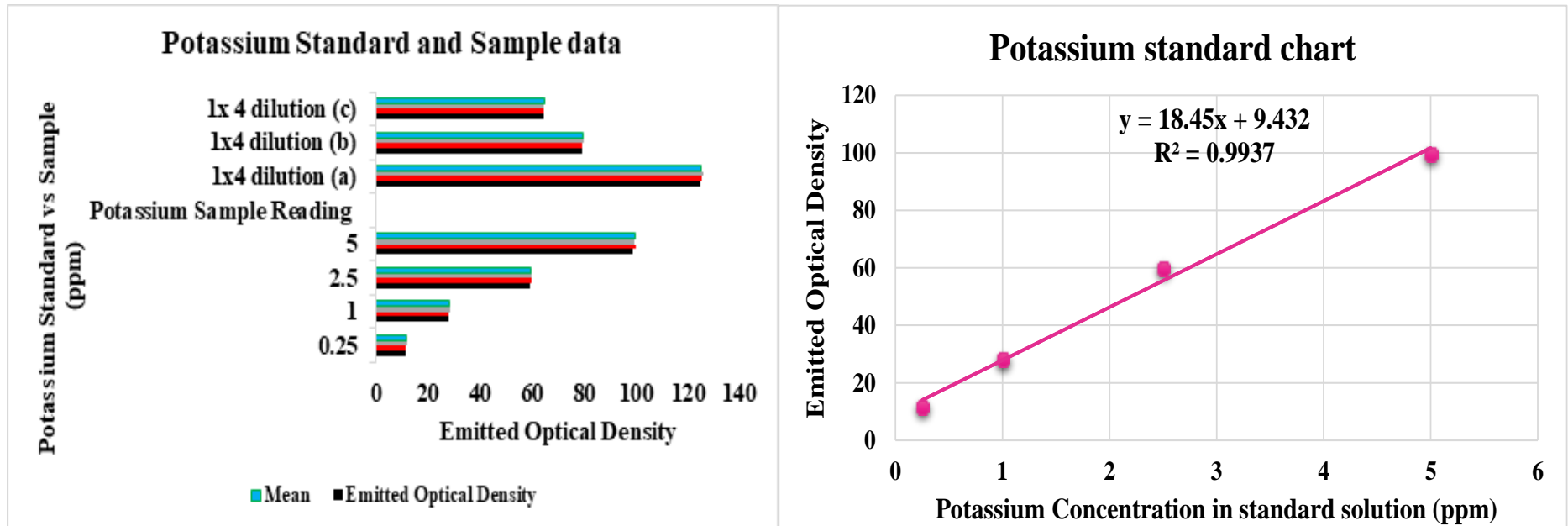
Figure 0-3: 21-30-Potassium and sodium determination using Flame Photometer. 31-38. Phosphorus and sulfur determination using U-V Spectrophotometer. 39. Potassium dichromate for Total Organic Carbon (TOC) determination and 40. Standard chart from U-V for TOC.

APPENDIX B: Sample weights and pH as recorded during experiments

<i>Parameter</i>	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Wet weight (g)	193.567	183.949	187.6	213.27	214.240
Dry weight at 60 ⁰ c	59.863	57.705	56.025	62.163	60.259
Dry weight at 105 ⁰ C	55.899	54.629	52.331	58.149	56.324
pH fresh (Ratio 1:1)	4.66	5.61	5.77	5.19	5.22

APPENDIX C: Standard and sample data versus charts used in compositional determination

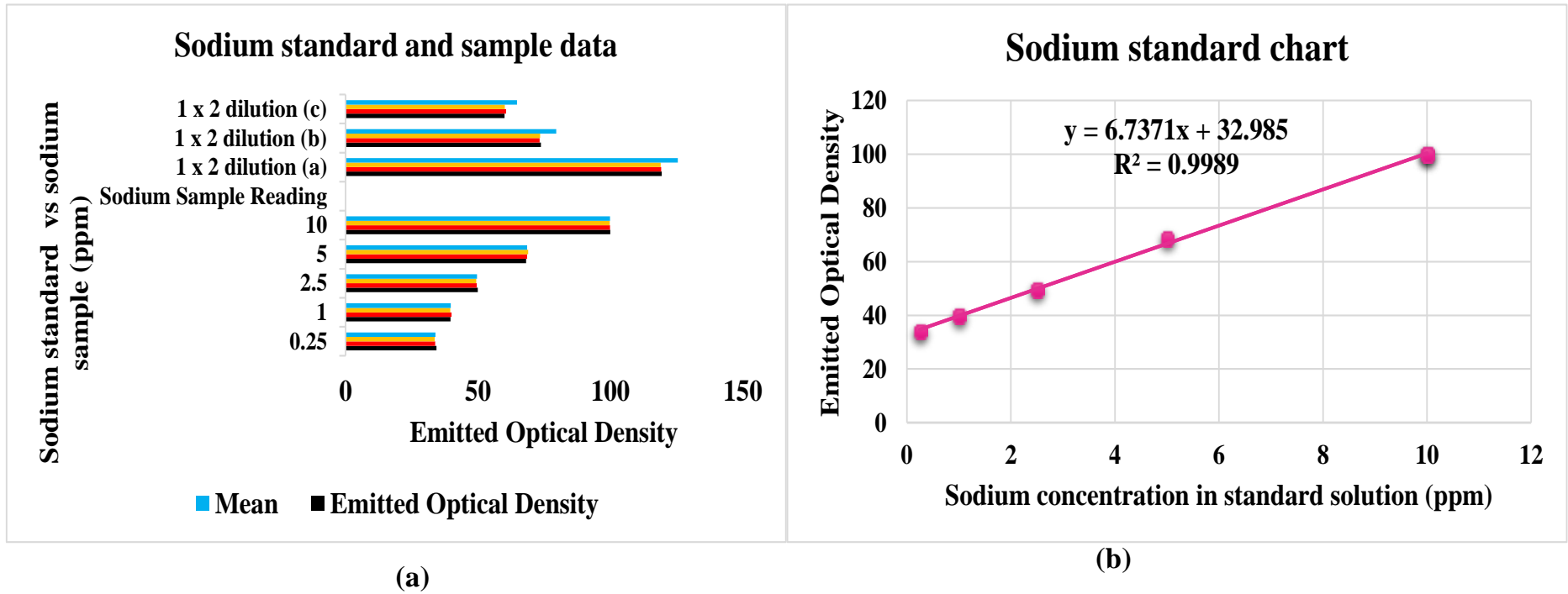
i. Potassium



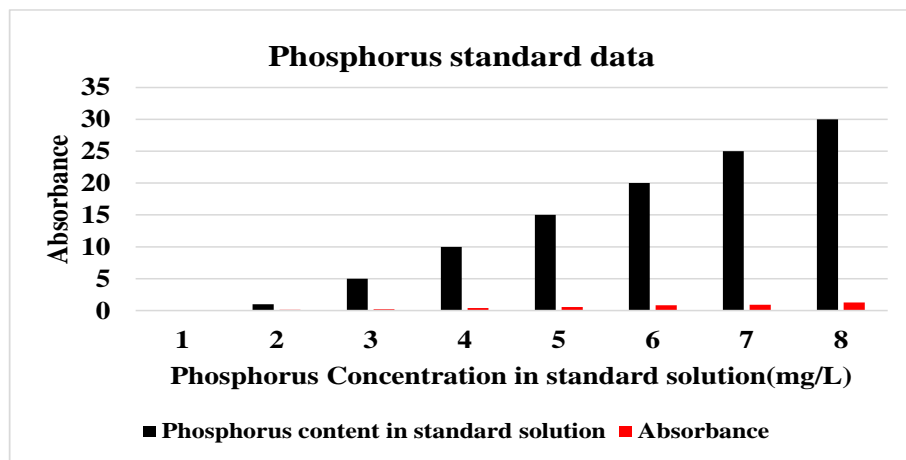
(a)

(b)

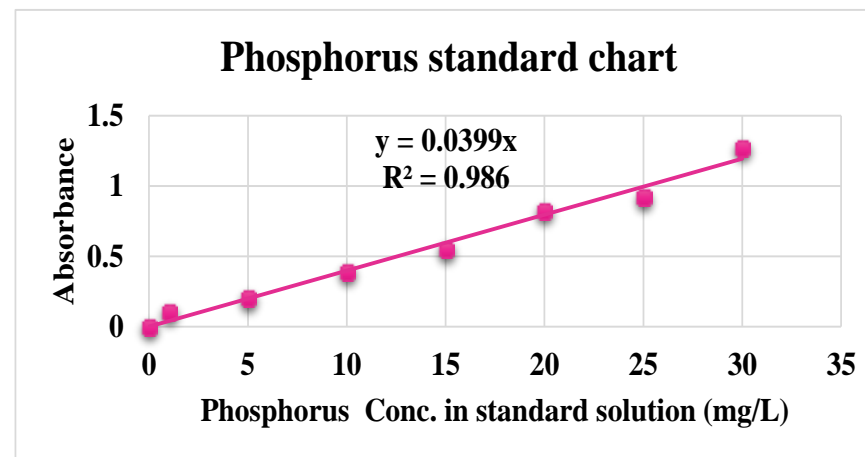
ii. Sodium



iii. Phosphorus

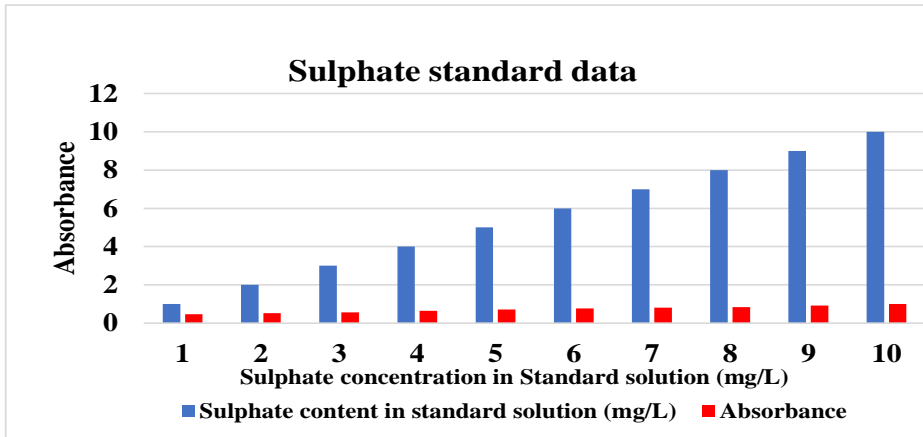


(a)

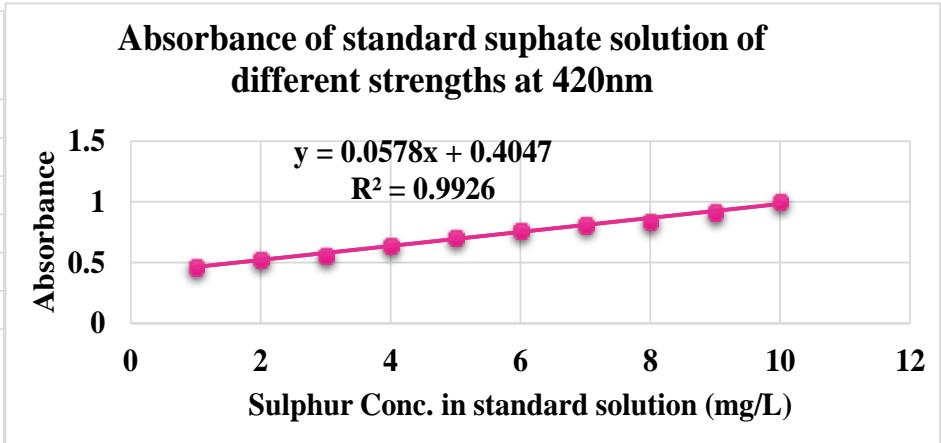


(b)

iv. Sulfur



(a)



(b)

APPENDIX D: Food waste Characterization results.

PARAMETER	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean
pH	4.6600	5.6100	5.7700	5.1900	5.2200	5.2900
Moisture Content (MC) (%)	5.9433	5.1700	6.1733	6.2200	6.5133	6.0040
Total Solid (%)	94.0567	94.2333	93.3400	93.4800	93.2867	93.6793
Volatile Solid (%)	85.8767	84.6800	82.6200	86.8633	81.5700	84.3220
Ash (%)	2.2367	4.6467	7.3167	3.40667	3.6133	4.2440
Fixed Carbon (%)	6.2212	5.473	5.0633	4.43	6.116	5.434
Nitrogen (%)	1.8177	6.8800	2.6900	1.8900	4.6700	3.5899
C/N	6.5395	1.5512	3.7357	5.1551	3.1728	4.0309
Crude Protein (%)	11.3604	43.0033	16.8367	11.7967	29.1867	22.4366
Crude Lipids (%)	12.5133	11.3700	14.4167	13.5933	8.6467	12.1080
Total Organic Carbon (%)	37.0937	36.5733	46.9833	51.6000	47.7233	43.9947
Potassium (%)	0.7890	1.5633	0.2067	0.2267	0.2133	0.5998
Sodium (%)	1.2346	1.3133	1.0433	1.3433	1.2267	1.2322
Calcium (%)	0.1856	0.0977	0.1930	0.1440	0.24867	0.1738
Lithium (%)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Barium (%)	Undetected	Undetected	Undetected	Undetected	Undetected	-
Phosphorus (%)	0.3001	0.3667	0.4500	0.2600	0.7267	0.4207
Sulphur (%)	0.0008	0.0006	0.0009	0.0001	0.0008	0.0007
Hydrogen	8.7972	8.9539	8.6717	9.1485	10.6927	9.2528
Oxygen	50.0528	42.9561	34.3383	33.9515	33.3073	38.9272

APPENDIX E: Food waste characterization results compared with other related studies

Parameter	This study	Other studies			
		(Abdelaal et al., 2019)	(Singh et al., 2020)	(Suarez et al., 2022)	(Slopiecka et al., 2022)
pH	5.2900	-	-	-	5.88
Moisture Content (MC) (%)	6.0040	-	11.312	-	-
Total Solid (%)	93.6793	32.5	-	-	64.84
Volatile Solid (%)	84.3220	85.9	73.262	67.6	44.18
Ash (%)	4.2440	6.0	3.304	11.8	-
Fixed Carbon (%)	5.434	8.1	12.122	13.3	-
Nitrogen (%)	3.5899	3.4	2.89	1.9	-
C/N	4.0309	-	-	-	15.9
Crude Protein (%)	22.4366	-	-	-	15.59
Crude Lipids (%)	12.1080	-	-	-	19.05
Total Organic Carbon (%)	43.9947	49.3	45.23	44.5	39.5
Potassium (%)	0.5998	-	-	-	-
Sodium (%)	1.2322	-	-	-	-
Calcium (%)	0.1738	-	-	-	-
Lithium (%)	0.0001	-	-	-	-
Barium (%)	Undetected	-	-	-	-
Phosphorus (%)	0.4207	-	-	-	-
Sulphur (%)	0.0007	-	-	0.2	-
Hydrogen (%)	-	7.0	6.92	6.2	-
Oxygen (%)	-	34.2	44.96	35.4	-

APPENDIX F: ANOVA

Analysis of Variance (ANOVA)						Proximate and mineral Model Summary			
Source	DF	Adj SS	Adj MS	F-Value	P-Value	S	R ²	R ² (adj)	R ² (pred)
<i>Moisture Content (%)</i>									
Factor	5	147.40	29.4808	46.80	0.000	0.793694	0.9070	88.76%	85.46%
Error	24	15.12	0.6299						
Total	29	162.52							
<i>Total Solids (%)</i>									
Factor	5	56413.6	11282.7	18394.58	0.000	0.783180	0.9997	99.97%	99.96%
Error	24	14.7	0.6						
Total	29	56428.3							
<i>Volatile Solids (%)</i>									
Factor	5	45562.6	9112.53	2390.92	0.000	1.95226	0.9980	99.76%	99.69%
Error	24	91.5	3.81						
Total	29	45654.1							
<i>Ash (%)</i>									
Factor	5	65.69	13.138	4.53	0.005	1.70342	0.4854	37.82%	19.59%
Error	24	69.64	2.902						
Total	29	135.33							
<i>Fixed Carbon (%)</i>									
Factor	5	641.52	128.304	37.33	0.000	1.85393	0.8861	86.23%	82.20%
Error	24	82.49	3.437						
Total	29	724.01							
<i>Nitrogen (%)</i>									
Factor	5	49.77	9.955	2.80	0.040	1.88665	0.3681	23.65%	1.27%
Error	24	85.43	3.559						

APPENDIX G:PUBLICATION

<https://www.sciencedirect.com/science/article/pii/S2772427125000051?via%3Dihub>

[https://kwnsfk27.r.eu-west-](https://kwnsfk27.r.eu-west-1.awstrack.me/L0/https:%2F%2Fdoi.org%2F10.1016%2Fj.nexus.2025.100364/1/01020194f24585bc-7f7151cb-945b-4e51-ace2-49a702a2b327-000000/6fmldkPScyDpYGD1d2VGT-42kBY=412)

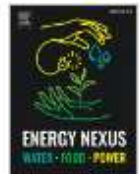
[1.awstrack.me/L0/https:%2F%2Fdoi.org%2F10.1016%2Fj.nexus.2025.100364/1/01020194f24585bc-7f7151cb-945b-4e51-ace2-49a702a2b327-000000/6fmldkPScyDpYGD1d2VGT-42kBY=412](https://kwnsfk27.r.eu-west-1.awstrack.me/L0/https:%2F%2Fdoi.org%2F10.1016%2Fj.nexus.2025.100364/1/01020194f24585bc-7f7151cb-945b-4e51-ace2-49a702a2b327-000000/6fmldkPScyDpYGD1d2VGT-42kBY=412)





[Download full issue](#)



Energy Nexus
Volume 17, March 2025, 100364



Characterization of food wastes from the hotel industry as a potential feedstock for energy production

Emily Machuma Muchele^a, Booker Osodo^a, Isaiah Omosa^b,
Emmanuel Yeri Kombe^a  

- ^a Department of Energy, Gas and Petroleum Engineering, Kenyatta University, P.O. BOX 43844-00100, Nairobi, Kenya
- ^b Department of Civil Engineering, Kenyatta University, P.O BOX 43844-00100, Nairobi, Kenya

APPENDIX H: RESEARCH APPROVAL FROM GRADUATE SCHOOL



KENYATTA UNIVERSITY
OFFICE OF THE EXECUTIVE DEAN, GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Website: www.ku.ac.ke

Internal Memo

FROM: Executive Dean, Graduate School **DATE:** 26th January, 2023
TO: Ms. Emily Machuma Muchele **REF:** J104/CTY/FT/20419/2020
C/o Department of Energy Technology

SUBJECT: APPROVAL OF RESEARCH PROPOSAL

=====

This is to inform you that Graduate School Board, at its meeting on 18th January, 2023, approved your Research Proposal for the M.Sc. Degree entitled, "Simulation and Optimization of Biohydrogen Production Using Food Wastes from the Hotel Industry in Nairobi City County, Kenya."

You may now proceed with your Data collection, subject to clearance with the Director General, National Commission for Science, Technology & Innovation.

As you embark on your data collection, please note that you will be required to submit to Graduate School completed Supervision Tracking and Progress Report Forms per semester. The forms are available at the University's Website under Graduate School webpage downloads.

Also, please ensure that you publish article(s) from your thesis before submitting it to Graduate School for examination as per the Commission for University Education and Kenyatta University guidelines

Thank you.


REUBEN MURIUKI
FOR: EXECUTIVE DEAN, GRADUATE SCHOOL

CC. Chairman, Department of Energy Technology
Supervisors:

1. Dr. Booker Osodo
C/o Department of Energy Technology
Kenyatta University
2. Dr. Isaiah Omosa
C/o Department of Civil Engineering
Kenyatta University

APPENDIX I: RESEARCH AUTHORIZATION FROM GRADUATE SCHOOL



KENYATTA UNIVERSITY OFFICE OF THE EXECUTIVE DEAN, GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke

Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Our Ref: J104/CTY/PT/20419/2020

DATE: 26th January, 2023

Director General,
National Commission for Science, Technology
and Innovation
P.O. Box 30623-00100
NAIROBI

Dear Sir/Madam,

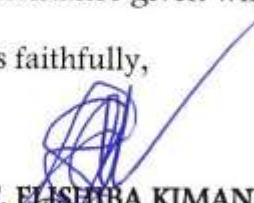
**RE: RESEARCH AUTHORIZATION FOR MS. EMILY MACHUMA MUCHELE –
REG. NO. J104/CTY/PT/20419/2020**

I write to introduce Ms. Emily Machuma Mucheke who is a Postgraduate Student of this University. She is registered for M.Sc. degree programme in the Department of Energy Technology.

Ms. Mucheke intends to conduct research for a M.Sc. thesis Proposal entitled, “Simulation and Optimization of Biohydrogen Production Using Food Wastes from the Hotel Industry in Nairobi City County, Kenya.”

Any assistance given will be highly appreciated.

Yours faithfully,


PROF. ELISHBA KIMANI
EXECUTIVE DEAN, GRADUATE SCHOOL

020/8704150

APPENDIX J: RESEARCH LICENSE FROM NACOSTI

 REPUBLIC OF KENYA	 NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION
Ref No: 163151	Date of Issue: 07/March/2023
RESEARCH LICENSE	
	
<p>This is to Certify that Ms.. EMILY MACHUMA MUCHELE of Kenyatta University, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Nairobi on the topic: Simulation and Optimization of Biohydrogen Production using Food Wastes from the Hotel Industry in Nairobi City County, Kenya for the period ending : 07/March/2024.</p>	
License No: NACOSTI/P/23/24227	
163151 Applicant Identification Number	 Director General NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION
	Verification QR Code
	
<p>NOTE: This is a computer generated License. To verify the authenticity of this document, Scan the QR Code using QR scanner application.</p>	
See overleaf for conditions	

The National Commission for Science, Technology and Innovation, hereafter referred to as the Commission, was established under the Science, Technology and Innovation Act 2013 (Revised 2014) herein after referred to as the Act. The objective of the Commission shall be to regulate and assure quality in the science, technology and innovation sector and advise the Government in matters related thereto.

CONDITIONS OF THE RESEARCH LICENSE

1. The License is granted subject to provisions of the Constitution of Kenya, the Science, Technology and Innovation Act, and other relevant laws, policies and regulations. Accordingly, the licensee shall adhere to such procedures, standards, code of ethics and guidelines as may be prescribed by regulations made under the Act, or prescribed by provisions of International treaties of which Kenya is a signatory to
2. The research and its related activities as well as outcomes shall be beneficial to the country and shall not in any way;
 - i. Endanger national security
 - ii. Adversely affect the lives of Kenyans
 - iii. Be in contravention of Kenya's international obligations including Biological Weapons Convention (BWC), Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), Chemical, Biological, Radiological and Nuclear (CBRN).
 - iv. Result in exploitation of intellectual property rights of communities in Kenya
 - v. Adversely affect the environment
 - vi. Adversely affect the rights of communities
 - vii. Endanger public safety and national cohesion
 - viii. Plagiarize someone else's work
3. The License is valid for the proposed research, location and specified period.
4. The license any rights thereunder are non-transferable
5. The Commission reserves the right to cancel the research at any time during the research period if in the opinion of the Commission the research is not implemented in conformity with the provisions of the Act or any other written law.
6. The Licensee shall inform the relevant County Director of Education, County Commissioner and County Governor before commencement of the research.
7. Excavation, filming, movement, and collection of specimens are subject to further necessary clearance from relevant Government Agencies.
8. The License does not give authority to transfer research materials.
9. The Commission may monitor and evaluate the licensed research project for the purpose of assessing and evaluating compliance with the conditions of the License.
10. The Licensee shall submit one hard copy, and upload a soft copy of their final report (thesis) onto a platform designated by the Commission within one year of completion of the research.
11. The Commission reserves the right to modify the conditions of the License including cancellation without prior notice.
12. Research, findings and information regarding research systems shall be stored or disseminated, utilized or applied in such a manner as may be prescribed by the Commission from time to time.
13. The Licensee shall disclose to the Commission, the relevant Institutional Scientific and Ethical Review Committee, and the relevant national agencies any inventions and discoveries that are of National strategic importance.
14. The Commission shall have powers to acquire from any person the right in, or to, any scientific innovation, invention or patent of strategic importance to the country.
15. Relevant Institutional Scientific and Ethical Review Committee shall monitor and evaluate the research periodically, and make a report of its findings to the Commission for necessary action.

National Commission for Science, Technology and
Innovation (NACOSTI),
Off Waiyaki Way, Upper Kabete,
P. O. Box 30623 - 00100 Nairobi, KENYA
Telephone: 020 4007000, 0713788787, 0735404245
E-mail: dg@nacosti.go.ke
Website: www.nacosti.go.ke