Agricultural Biomass as A Sustainable Renewable Energy Source: A Life Cycle Assessment

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DEDICATION

“I express my profound gratitude to the Almighty, "ALLAH," for endowing me with the courage and determination to complete this endeavor, seeking strength through the blessings of our Holy Prophet (PBUH), even in the face of numerous challenges. It would not have been possible without the support of my parents and siblings whose tremendous support and cooperation led me to this wonderful accomplishment.”

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LIST OF ABBREVIATIONS AND ACRONYMS

GHG	Greenhouse gases
RS	Rice straw
S1	Scenario 1 (RS open burning)
S2	Scenario 2 (electricity production from RS & replace coal electricity)
S3	Scenario 3 (electricity production from RS & replace Pakistan grid electricity)
S4	Scenario 4 (Briquette formation & replace wood open burning)
IPCC	Intergovernmental panel on climate change
GT	Giga tons
BF	Briquette fuel
CO_2 Eq.	Carbon dioxide equivalent
FAO	Food and Agriculture Organization
GWP	Global warming potential
SDGs	Sustainable development goals
ISO	International organizations for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory analysis
BF	Briquette fuel
FU	Functional unit
NMVOC	Non-methane volatile organic compounds
PBS	Pakistan Bureau of Statistics

ADP	Abiotic depletion potential
ODP	Ozone depletion potential
HTP	Human toxicity potential
AP	Acidification potential
EP	Eutrophication potential
PCOP	Photochemical oxidation potential
FAEP	Freshwater aquatic ecotoxicity potential
MAEP	Marine aquatic ecotoxicity potential
TEP	Terrestrial ecotoxicity potential
OB	Open Burning
Eco	Electricity from Coal
ERs	Electricity from RS Direct Combustion
EGr	Pakistan Grid Mix electricity
BF	Briquette Fuel
WOB	Wood open burning

ABSTRACT

Rice straw (RS) in-situ burning is commonly practiced globally and has adverse environmental impacts not only on the climate it has negative consequences on air quality, human health, and multiple other adverse consequences. The potential way to halt greenhouse gas (GHG) emissions is the production and use of bioenergy as an alternative to conventional non-renewable energy sources. This study presents the application of life cycle assessment methodology for assessing the environmental impacts of open burning (S1), electricity production by direct combustion of RS and replacing coal-based electricity (S2), electricity production by direct combustion of RS and replacing Pakistan grid mix electricity (S3) and briquette production its combustion and replacing wood burning in three brick stoves (S4). The current study aims to perform a LCA of bioenergy production from rice straw and to identify the most sustainable choice among these proposed scenarios. A total of 11 mid-point indicators were analyzed. The GHG saving comparison of rice straw based electricity with coal shows the emission of GHG can be reduced by 1.82 kg CO_2 eq per kWh of electricity generation. All three scenarios except S1 show net reducing GHG balances. The results shows that S2 shows maximum reduction trend in term of all mid-point categories except human and terrestrial ecotoxicity. While S2 has the highest GHG reduction (1776 kg CO_2 eq/ton RS) and is considered as the most sustainable process gaining negative values in 11 out of 11 environment impact categories and the highest reduction value was in marine water aquatic ecotoxicity potential (2933635.5 kg 1,4-DB-eq in S2). The energy from biomass is a promising way to offset emissions from fossil fuel and in-situ burning of rice straw. Moreover, biomass is an environmentally friendly source of energy that offers various benefits, including carbon neutrality and large availability in Pakistan. This study demonstrates an effective approach to encourage the utilization of surplus agricultural residue to generate products such as electricity and biofuels thereby promoting a circular economy methodology toward agricultural crop residue management and achieving sustainable development goals (SDGs). Consequently, these practices offer greater advantages in terms of both environmental impact and economic viability and contribute to the reduction of different impact indicators like global warming potential (GWP), acidification, resource depletion, eutrophication, photochemical and ozone depletion potential.

Keywords: Rice straw, direct combustion, life cycle assessment, environmental impact assessment, mid-point impact indicators, briquette fuel, electricity, global warming potential, sustainable development goals, greenhouse gas.

CHAPTER 1

INTRODUCTION

1.1 Background

The term "climate change" is the alteration of climatic patterns due to greenhouse gases (GHG) emissions. Global warming is primarily caused by GHG emissions, which trap heat in the Earth's atmosphere. Natural processes and anthropogenic activities are the principal cause of these emissions. Anthropogenic activities are mostly related to energy, industry sectors, agroforestry, land use, and changes in land-use practices. Whereas natural processes include forests, earthquakes, oceans, permafrost, wetlands, and volcanoes (Fawzy et al., 2020). Climate change poses real danger to food security and agriculture, with developing countries such as Pakistan expected to bear the brunt of its consequences. Based on the global climate risk index, Pakistan placed at the fifth position among the countries that are most susceptible to the impacts of climate change. The nation has already experienced an increase in climatic extremes, such as heat waves, floods, droughts, and water shortages. The lengthy drought from 1999 to 2003, the heatwaves in Karachi, and the floods between 2010 and 2014 are three of Pakistan's most frequent and extreme weather phenomena (Shah et al., 2022) along with the recent flood of 2022 in which one-third of the country was under flood water. (IPCC 2014) has configured out the main GHGs are CO_2, CH_4 and N_2O (Das et al., 2020; Shen et al., 2015; IPCC 2007). Moreover, the IPCC statically deduced the global anthropogenic GHG emissions hiked by 10 Gt CO_2 eq annually between 2000 and 2010, with the industrial sector contributing 30% of this hike, followed by transportation (11%), and buildings (3%) while the energy sector is the top contributor with contributions of 47% towards greenhouse gas emissions (IPCC 2014). While 2019 stats show a bit of a shift as the energy sector contributed 34% of GHG global emissions, 24% by industry, 22% from agriculture, forestry, and other land use changes while the remaining 15% and 6% have come from the transport and building sectors respectively (Calvin et al., 2023).

Recently in an IPCC report published in 2018, an alarming scenario has been reported that is associated with an increase in temperature by 1.5 and 2 degrees Celsius. In this report, the adverse impacts of global warming are discussed concerning human health, urbanization, freshwater resources, ecosystems, food security, and food production systems along with poverty and shifting community structures. Moreover, the influence of climate change on important economic sectors like transportation, energy, and tourism was also examined in the research. The majority of the dangers associated with the consequences studied are lower at a hike of 1.5 degrees Celsius than at 2 degrees (Fawzy et al., 2020; IPCC, 2022).

1.2 Renewable Energy

Being an agrarian and the 6th most populous country (Azhar et al., 2019; Irfan et al., 2020) the power sector of Pakistan is largely dependent on nonrenewable energy sources. It is quite emphasized the agriculture and energy sectors jointly account for 91% of total GHG emissions in the country. However, 46% are mainly caused by the agricultural sector while energy sector contributing 45 to total GHG emissions during 2017-18 (The Govt. of Pakistan 2021 report.) .The country has rich potential for bioenergy from multiple sources therefore, the lack of policy and technological innovation halts the way to moving towards renewable energy options (Uzair et al., 2020; Zuberi et al., 2015). Considering major issues like fossil fuels depletion, climate change, and the current shift of power production towards carbon-neutral sources, the government is keen to have at least 20% and 30 % of the grid mix electricity from renewable sources by 2025 and 2030 respectively. The depletion of non-renewable fuels with the unpredictable threat of climate change has compelled the global community to seek alternative solutions and take stringent measures to overcome these major issues (Fawzy et al., 2020; ARE Policy, 2019; Irfan et al., 2020; Mahmood & Gheewala, 2020; Osman et al., 2021).

According to the 2019 ARE policy (alternative and renewable energy policy) report the government of Pakistan is keen to look for renewable energy technologies like energy from biomass, wind, solar, tidal, hydrogen, geothermal, and waste to enhance the portion of renewable energy in the grid mix (Osman et al., 2021; Quereshi et al., 2020). The global energy mix was composed of 2% biofuels, 10% nuclear, 64% fossil fuels, and 24% renewables in 2018 and a similar trend is observed for Pakistan during year 2020 which has 61% share from non-renewable sources 29% from hydro, 4% nuclear and 6% others.

As a signatory of the Kyoto Protocol and the Paris Agreement, Pakistan is committed to achieving the United Nations sustainable development (SDGs) goals by keeping in limit the increase in temperature below 1.5-2 °C. Moreover, the per capita energy consumption in Pakistan is considerably below the worldwide average with 457 kWh in contrast to 2892 kWh annually (Alengebawy et al., 2022; Durrani et al., 2021). However, the country is still vulnerable to energy and climate change crises.

Pakistan has the rich potential of bioenergy from second-generation biofuels to offset GHG emissions. Due to less carbon emission and its renewable nature, electricity from biomass is in the limelight.

1.3 Rice Straw as Energy Source

The byproduct of harvesting rice is rice straw. Like India, Thailand, Vietnam, and Malaysia, rice straw is also commonly available in Pakistan and research has been carried out by different authors on rice straw utilization as fertilizer, fuel, power generation, and briquettes formation (Kami Delivand et al., 2012; Mahmood & Gheewala, 2020; Nguyen et al., 2016; Saba et al., 2020; Shafie et al., 2014; Silalertruksa & Gheewala, 2013; Soam et al., 2017; Suramaythangkoor & Gheewala, 2008, 2010). According to the database of the FAO, the quantity of paddy rice produced on an annual basis reached a staggering 782 million tons in the year 2018 (Moliner et al., 2020). Pakistan is 4th largest exporter and stands at 10th place among the largest rice-producing nations globally (Ghani et al., 2023). According to (Uzair et al., 2020) the annual production of 11596 thousand MT of rice straw in Pakistan can potentially generate 1723 MW of electricity. Moreover, the country is facing challenges in agricultural crop residue management due to poor management practices. So, the farmers burn crop residue to make their land ready for the coming crop (Azhar et al., 2019; Mahmood & Gheewala, 2020; Prasad et al., 2020; Silalertruksa & Gheewala, 2013; Soam et al., 2017).

1.4 Open Burning of Rice Straw

Rice straw in-situ burning is a very commonly practiced globally that has adverse impacts not only on the climate although it has negative consequences on air quality, human health, vital nutrients (NPK) loss, cryosphere ice melting and it also kills soil microorganisms that are necessary for plant growth (Mahmood & Gheewala, 2020; Nguyen et al., 2016; Prasad et al., 2020; Shafie et al., 2014; Soam et al., 2017; Suramaythangkoor & Gheewala, 2010).

The air pollutant emissions factors for open burning of one-ton rice straw are taken from (Azhar et al., 2019) and their 100 years global warming potential (GWP100) is calculated as 1406 kg CO_2 equivalent.

Table 1.1. GWP-100 from open burning of rice straw

Pollutants	Emissions (kg/ton) [a]	GWP (kg CO_2 Eq.) [b]	100-year GWP
CO_2	1105.2	1	1105.2
CO	53.2	1.8*	111.72
N_2O	0.07	298	21
CH_4	5.82	25	168.78

Source: [a] (Azhar et al., 2019) [b] (IPCC 2014) (Corbett et al., 2011) * (IPCC 2007)

1.5 Energy from Biomass Global Perspective

The energy from biomass is a promising way to offset emissions from fossil fuel and in-situ burning of rice straw (Alengebawy et al., 2022; Shafie et al., 2014). Moreover, Biomass is an environmentally friendly source of energy that offers various benefits, including carbon neutrality and large availability within a short period. Another important thing it is considered a renewable energy source. (M. Singh et al., 2021). At present, a significant amount of agricultural residue is either burned on fields or simply misspend without beneficial uses. However, by burning in boilers, this biomass can be effectively utilized and has the potential to generate electricity at a lower cost (Uzair et al., 2020). Around the globe, there are many technologies and processes that are currently deployed like the production of biogas, syngas, electricity by direct combustion, gasification, pyrolysis, briquettes fuel, biomass to fertilizer, ethanol from straw, and cogeneration (Alengebawy et al., 2022; Chen et al., 2020; Cheng et al., 2020; Dyjakon et al., 2019; Ekman et al., 2013; Freitas et al., 2022; Kami Delivand et al., 2012; Lask et al., 2020; Mahmood & Gheewala, 2020; Osman et al., 2021; Prasad et al., 2020; Quereshi et al., 2020; Saba et al., 2020; Shafie et al., 2014; J. Singh & Gu, 2010; Soam et al., 2017; Suramaythangkoor & Gheewala, 2010).

1.6 Research Objectives

The primary objective of this research is to identify the most eco-friendly method for utilizing rice straw by applying the life cycle assessment (LCA) technique. Specifically, the research aims to:

1- Estimate the environmental impact of rice straw open burning.
2- Estimate the environmental impact off set by replacing the rice straw open burning by scenarios considering its conversion into energy, replacing conventional energy resources.

CHAPTER 2

LITERATURE REVIEW

Since Pakistan has huge potential for agricultural biomass and is unable to manage and utilize it properly however the regulatory authorities are looking for alternative and sustainable practices to manage this waste and to overcome electricity shortage issues. This study is one of the efforts to look for sustainable practices to manage this biomass which at present contributes towards the huge number of GHG emissions. The alternative crop usage scenarios assumed in this study not only help to eradicate residual biomass mismanagement, these will also be sustainable options to generate electricity. A comprehensive literature review was conducted before this research.

2.1 Challenges of Conventional Energy Sources

Conventional energy sources (gas, oil and coal) do meet the energy demands (Chauhan et al., 2011) however, this comes after the great cost of increasing greenhouse gas emissions into the atmosphere, leading to climate change. Developing countries depend on conventional energy sources to meet their growing energy demands. These are not only limited to the developing countries however, the developed countries are even using more fossil fuels than the developing countries. Here are some stats from the USA for the year 2020 which explain how heavily they rely on non-renewable energy sources even after more sustainable solutions. Petroleum, Natural gas and Coal were the main fossils used by the USA to meet the energy demands. Their percentage of usage was 44%, 43% and 13% respectively (An et al., 2022). The increasing population and advancements in human civilization have led to a continuous rise in global energy demand over the past four decades, as evidenced by statistics showing a 2.8% annual increase in global energy demand from 1978 to 2017 (Abbas et al., 2022). The depleting conventional energy sources, deleterious environmental impacts from these non-renewable energy sources, carbon emissions and global warming are raising alarm and paving the way for renewable energy sources (Abbas' et al., 2022; Olio & Abdelkareem, 2022).

2.2 Alternative to Conventional Energy Sources

Many energy sources are under consideration as renewable energy sources like wind, solar, and hydro. These are considered natural sources. Compared to the depleting sources, these are non-depleting and cause less carbon emissions into the atmosphere. Apart from these, there is another field of renewable energy has the potential to produce energy and also credible to manage biomass waste. Energy from biomass is regarded as a highly attractive renewable energy source due to its role in managing waste (Olabi & Abdelkareem, 2022). Bioenergy from biomass is a promising way to utilize waste and combat climate change. This waste utilization is also potent in creating employment opportunities for the locals. More importantly this waste utilization in a positive manner offsets the open burning emission to get rid of any type of agriculture biomass waste (Kami Delivand et al., 2012). Agriculture waste cover different types of waste like sugarcane waste, rice straw, rice husk, wheat straw, and tree leaves. Many studies have been conducted by different authors to evaluate the impacts of utilizing rice straw especially for the energy generation (Moliner et al., 2020; Shafie et al., 2014). China is using biomass for energy generation and contributing to the national grid mix by adding 94 TWh of electricity from biomass alone (Abbasi et al., 2022). Currently, many countries practice open burning of crop residue in the fields to prepare the land for the next crop. In this study focused biomass will be rice straw.

2.3 Rice Straw Production in Pakistan and Management Practices

Pakistan is predominantly an agrarian country, with the agricultural sector being the primary contributor to its economy. According to (Uzair et al., 2020) as per the Pakistan Economic Survey Report of 2019-20, the agriculture sector accounts for a share of 25% of the Gross Domestic Product (GDP), making it a significant component of Pakistan's economic landscape. Additionally, it employs a workforce of 42.3%, which highlights the sector's importance as a source of employment generation for the country. Moreover, the agricultural sector also plays a vital role in earning foreign exchange for Pakistan, with a contribution of 75% from its exports. Hence, the agricultural sector in Pakistan is not only vital for the country's economic growth although it can also serve as a significant source of income for a considerable percentage of the population while making significant contributions to foreign exchange reserves. Table 2.1 below provides comprehensive information about the total area devoted to rice cultivation, along with the corresponding production figures for the last decade.

Table 2.1. Total area devoted to rice cultivation & production in Pakistan

Year	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21(P)
Area (10^3) Hectare	2571.2	2308.8	2789.2	2890.6	2739.5	2724.0	2900.6	2810.0	3034.0	3335.1
Production (10^3) tons	6160.4	5535.9	6798.1	7002.8	6801.3	6849.3	7449.8	7202.0	7413.7	8419.7

P= Provisional
Source: (Pakistan bureau of statistics, 2021)

The province of Punjab (Pakistan) has emerged as a significant contributor to the agricultural sector, primarily due to its favorable climate, soil fertility, and adequate water supply annually. The interplay of these factors has created ideal conditions for agricultural productivity, leading to higher yields and better-quality crops. So, the current study focuses exclusively on the Punjab province to look for potential energy sources. By concentrating on this specific region, the study aims to gain insights into the unique challenges and opportunities faced by farmers in Punjab to manage biomass and identify potential solutions that could help enhance the sector's productivity and sustainability in the long run.

Figure 2.1 shows the rice straw production across different cities of the Punjab province of Pakistan. According to the spatial distribution map it can be depicted that the Okara, Gujranwala, Sheikhupura, Hafizabad, Jhang, and Bahawalnagar districts can be seen as the potential districts for the setup of 200-300 MW of straw-based powerplants as these districts have the enormous potential to feed such big powerplants.

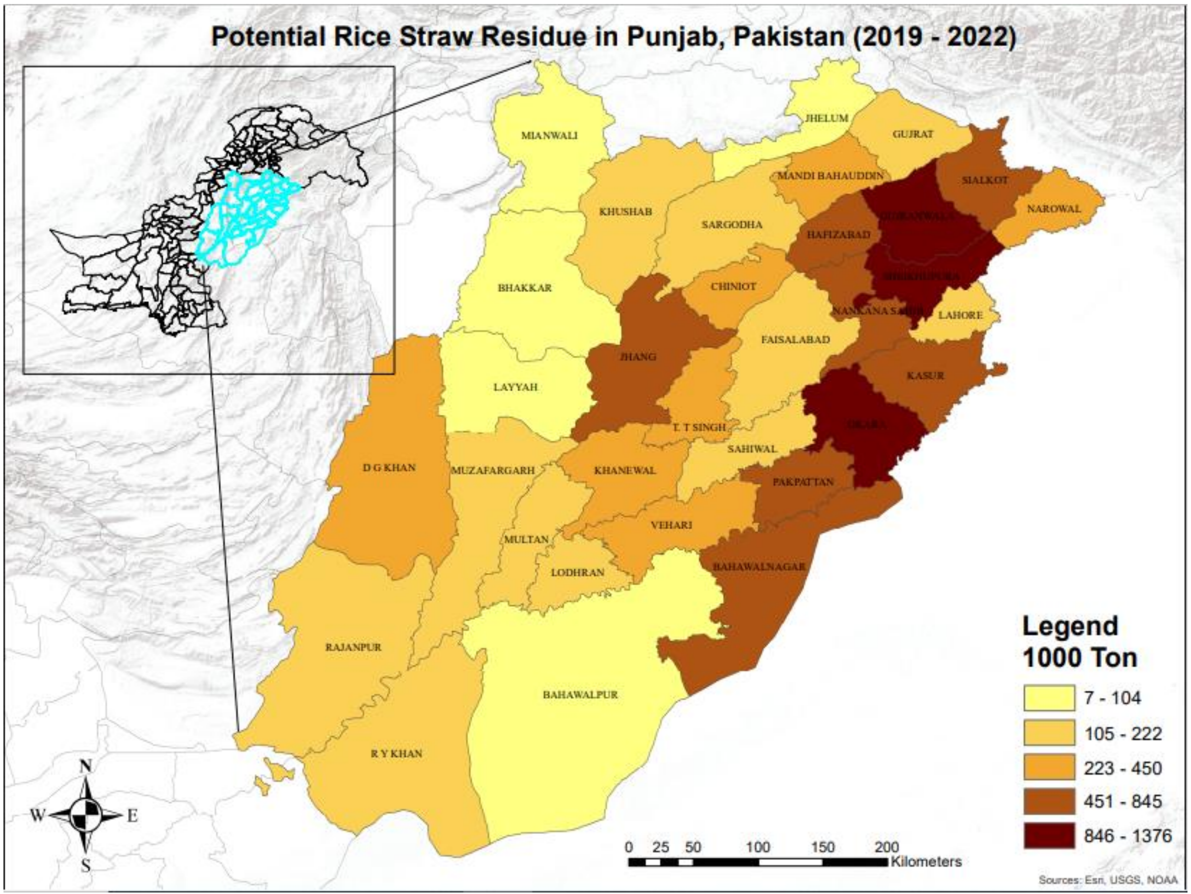

Figure 2.1. Rice straw's spatial distribution in Punjab, Pakistan (2019-2022)
Source: (Crop Reporting Service)

Many technologies rice straw utilization techniques are discussed above in the introduction section. According to (Uzair et al., 2020) electricity crisis is a significant issue in Pakistan as a country heavily relies on non-renewable fuels for energy production. However, the country can produce 16498MW of electricity from agricultural biomass. However, the current practices of rice straw management are to mostly open burn the rice straw in the field. So LCA was selected to analyze the environmental impacts of rice straw utilization for the energy generation purpose especially the conversion of rice straw to electricity by direct combustion and briquette formation.

2.4 Life Cycle Assessment as Tool

The analysis of the complicated interaction between anthropogenic activities and the surrounding environment can be effectively achieved with life cycle assessment (LCA). LCA is a tool for quantitative analysis related to various aspects of product development.

Furthermore, it serves as a valuable tool for assessing the environmental load resulting from the entire life cycle of a product. This makes it a powerful method for managing the environmental consequences of human activities. It is one of the most remarkable approaches to comprehensively assess the environmental concerns regarding the bioenergy production from rice straw, which is globally practiced to evaluate the environmental effects that arose from certain processes and is also helpful to compare different processes. Moreover, the management of a product from its initial creation to its eventual disposal is achieved through a set of managerial practices and organizational arrangements this process is known as life cycle management (Alengebawy et al., 2022; Chauhan et al., 2011; Freitas et al., 2022; Osman et al., 2021; Prasad et al., 2020; Shafie et al., 2014).

LCA is guided by four key principles adopting a life cycle perspective, prioritizing environmental concerns, utilizing a relative approach, and defining a functional unit (Chauhan et al., 2011)

The four integral parts of LCA

Goal and scope

Life cycle inventory

Impact assessment

Result and interpretation

2.4.1 Goal and Scope

System boundary and functional unit are the integral part of LCA goal and scope stage. According to (Cheng et al., 2020) the system's boundary can be treated as a black box, whereby the focus is on analyzing the resources and energy consumption within the system's input and output to obtain the desired results, without necessarily paying attention to the specific internal processes. The scenarios are considered to replace the in-situ burning of rice straw and prevent emissions from open burning. The boundary of the current study commences with the collection of rice straw. This portion is discussed briefly in chapter 3.

2.4.2 *Life cycle inventory*

The life cycle inventory (LCI) of any LCA study comprises collecting, organizing, and measuring the amount of energy and material needed across the product life cycle. The fundamental aspect of the LCA inventory is to create a list of data based on the functional unit (FU). This stage of collecting Life Cycle Inventory (LCI) data is among the most crucial and laborious tasks in conducting an LCA study, as inaccurate data can significantly impact the results.

2.4.3 *Impact assessment and methods*

Life Cycle Impact Assessment (LCIA) evaluates the environmental effects or load a product poses throughout its life cycle by converting its emissions into potential environmental midpoint indicators. It helps to identify the causes and impacts of these midpoint indicators and translates them into an impact profile. According to (Shafie et al., 2014) most LCA studies involving bioenergy production use the CML method for environmental impact investigations mainly caused by emissions of different gases. These studies used the CML method for Impact Assessment (Silalertruksa & Gheewala, 2013; A. Singh & Basak, 2019; Vicente Leme et al., 2021). This method was selected because the CML-IA (baseline) method develops the problem-focused (midpoint) approach. Moreover, the CML method is the most frequently used method of life cycle assessment of similar studies (Soam et al., 2017). Here is a reference to some similar studies conducted by authors (Shafie et al., 2014; Silalertruksa & Gheewala, 2013; Soam et al., 2017; Suramaythangkoor & Gheewala, 2011). (Osman et al., 2021) reviewed the 40 LCA studies of biomass conversion to biofuels. (Alengebawy et al., 2022). During the literature review, only one research of its kind was found for the Pakistan context that was conducted by (Mahmood & Gheewala, 2020). This was quite interesting as the author comparatively analyzed the three scenarios of rice straw utilization as open burning, power generation by direct burning and mulching. They concluded the rice straw direct combustion for energy generation was the most favorable option among others.

The current study aims to perform a LCA of rice straw utilization in sustainable ways. All the scenarios in this study focus on analyzing their potential for offsetting emissions from the in-situ burning of rice straw. As far as we know, this is the initial research that has employed the life cycle assessment methodology to evaluate these options together in one study specifically for Pakistan. This study demonstrates an effective approach to encourage the utilization of surplus agricultural residue to generate products such as electricity and biofuels thereby promoting a circular economy methodology toward agricultural crop residue management. Consequently, these practices offer greater advantages in terms of both environmental impact and economic viability (Moliner et al., 2020) and contribute towards achieving SDGs 7 and 13 ensuring access to affordable and clean energy, as well as taking action to combat climate change, respectively. This study will help decision makers to think about making investments in this technology.

CHAPTER 3

METHODOLOGY

3.1 Goal and Scope

The scenarios that will be discussed are scenario 1 (S1) is about the base case scenario of open burning of rice straw. 2nd scenario (S2) analyses electricity generation from rice straw by direct combustion and replacing coal based electricity. 3rd scenario (S3) discusses the potential impacts of generating electricity from rice straw by direct combustion and replacing the Pakistan grid mix electricity. The last scenario (S4) focused on briquette formation from straw and replacing open wood burning in three brick stoves for cooking or heating purposes.(Shafie et al., 2014).

3.1.1 Functional Unit

In the current study, 1 ton of rice straw is considered as the functional unit (FU). The LCA will be based on processing 1-ton straw for electricity and briquette fuel production. The selection of this functional unit is similar to previous LCA studies conducted by different authors (Alengebawy et al., 2022; Cheng et al., 2020; Kami Delivand et al., 2011; Mahmood & Gheewala, 2020; Silalertruksa & Gheewala, 2013; A. Singh & Basak, 2019; Soam et al., 2017).

3.1.2 System Boundary

The systematic diagram of the System boundary is shown in Figure. 3.1. To execute the LCA model accurately, a few assumptions were made, including the following:

The system boundary begins with the raking process, followed by baling. Loading comes after baling, and transportation follows thereafter. The collection stage is then completed, and the pre-treatment stage begins, involving the chopping of straw for briquette only.

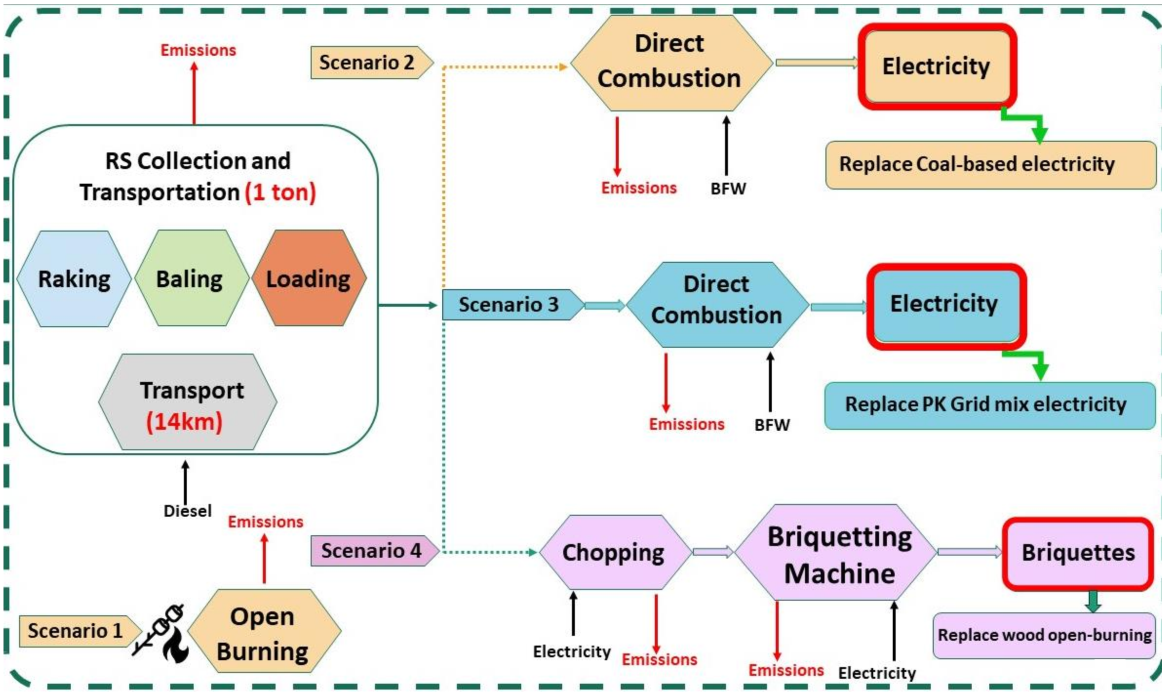

Figure 3.1. A systematic flow diagram of the system boundary for the LCA study.

3.2 Assumptions

- This LCA primarily evaluates the consequences of electricity and briquette fuel (BF) manufacturing processes, so the environmental impacts associated with infrastructure and maintenance of production technologies are excluded. Moreover, the impacts related to capital expenditures and human labor are also not part of this study (Alengebawy et al., 2022; Al-Mawali et al., 2021; A. Singh & Basak, 2019; Soam et al., 2017).
- The processing of rice straw is classified as an off-field management approach, this study does not address the environmental effects of cultivation and harvesting stages, (as we are not particularly sowing paddy for straw and energy generation purposes rather, we are dealing with the surplus straw that is causing severe consequences on the environment as well as land-use effects that occur prior to the collection phase (Alengebawy et al., 2022; A. Singh & Basak, 2019; Soam et al., 2017).

- The collected rice straw is considered sun-dried and is assumed to have moisture content within the range of 10-15%. (Shafie et al., 2014)
- The handling waste treatment scenario of end-products (ash) in the case of coal, rice straw, and briquette combustion is excluded from the system boundary of the study, as this study concludes with bioenergy and briquette utilization.
- All the calculations and assumptions are being made considering the powerplant of 10 MW. However, the environmental impacts of the power plant's infrastructure are not discussed in this study since the focus was only on the energy and material flow throughout the whole life cycle.
- Due to database limitation in SimaPro the open burning emissions and the boiler emissions factors are considered same and these emissions were taken from (Andreae & Merlet, 2001).
- The RS powerplant was selected to be located in Gujranwala.

3.3 Life Cycle Inventory (LCI)

The inventory data for this LCA is given in Table 3.1. Most of the data used is taken from various studies conducted by different researchers and additional data were acquired using the latest edition of the Ecoinvent 3.8 database.

Table 3.1. Inventory data to process 1 ton of rice straw.

LCA Stages	Ecoinvent process	Database source	Value used in SimaPro	Data source
Raking	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery |	Ecoinvent	17.97MJ	(Alengebawy et al., 2022)
Baling	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery |	Ecoinvent	110.9MJ	(Alengebawy et al., 2022)

Loading	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery |	Ecoinvent	31.74MJ	(Alengebawy et al., 2022)
Transportation	Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural |	Ecoinvent	14 tkm	Calculated
Water usage in electricity generation (cooling water)	Water, deionised {RoW}| market for water, deionised |	Ecoinvent	3.238 m^3 calculated	(Anna Delgado Martin et al., 2012)
Water requirement (losses+ boiler makeup)	Water, deionised {RoW}| market for water, deionised |	Ecoinvent	216.2 ltr calculated	(Anna Delgado Martin et al., 2012)
Chopping	Electricity, medium voltage {PK}| market for electricity, medium voltage |	Ecoinvent	16.50 kwh	(Alengebawy et al., 2022)
Coal Transportation	Transport, freight, lorry 3.5-7.5 metric ton, euro3 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton	Ecoinvent	840 tkm	Calculated
Briquetting machine	Electricity, medium voltage {PK}| market for electricity, medium voltage |	Ecoinvent	37.50 Kwh	(Alengebawy et al., 2022)

The diesel energy content was calculated on the base of the diesel energy coefficient value which is taken as 45 MJ/kg (SimaPro). To convert the amount of diesel from liters to kilograms, the specific density of the diesel used is 0.85 kilograms per liter (Gao & Xue, 2020; Godiganur et al., 2009).

Table 3.2. Rice straw-based fired boiler emission factors.

Gas emitted	Emission factor Kg/kwh
CO_2	1.94[a]
CO	0.0034 [a]
N_2O	0.0032 [a]
NO_x	9.00E-05 [a]
CH_4	0.0034 [a]
SO_x	0.0005 [a]

Source: [a] (Andreae & Merlet, 2001)

3.3.1 Preprocessing Stages

3.3.1.1 *Raking, baling and loading*

The process of raking, baling, and loading of rice straw are on-field activities. We focused our analysis on materials and factors that have significant environmental impacts. Therefore, we considered the diesel combustion that takes place in the engines of agricultural machinery used for all three processes, including the baler, tractor, and loader. These machines require diesel to perform their operations. So, the values for diesel requirements are based on the values reported in a study conducted by (Alengebawy et al., 2022). Subsequently, calculations were performed to incorporate the diesel requirement into the software database, which contains energy units specific to the utilization of diesel in agricultural machinery. As a result, the diesel amount must be converted to match these units. The specific diesel consumption for each activity for the selected functional unit, are given in Table 3.3.

Table 3.3. Diesel consumption for the preprocessing stages of 1 ton RS

Preprocessing stage	Raking	Baling	Loading
Diesel consumption (Liter)	0.47	2.9	0.83

3.3.2 Transportation

Rice straw transportation

The transportation of straw is a critical part of the LCA as it is necessary to transport the rice straw bales to the power plant. This involves using a tractor or a vehicle to transport the straw over a certain distance. The distance that the transportation vehicle needs to travel is calculated by identifying the catchment area that can provide enough straw to meet the needs of the 10MW biomass plant.

Equation 1 is used to find the circular catchment area (Silalertruksa et al., 2013)

Circular Catchment Area Calculation

$$\text{Circular Catchment area } (km^2) = \frac{Sd \times (1+Sl)}{ASY \times Af \times Ff \times C\eta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq\ 1.$$

Sd = Annual rice straw demand in tons (t)

Sl = Straw loss during collection and transportation (10%)(Silalertruksa et al., 2013).

ASY = Annual straw yield (138.5 t/km^2) this value is calculated from survey data.

Af = The availability factor refers to the proportion of land within a circular catchment area that is suitable for cultivating paddy rice (100%). (Mahmood & Gheewala, 2020)

Ff = The farmland factor is the amount of rice straw that is openly burnt in fields. This factor is important as it indicates the potential for using the burned rice straw as an alternative energy source. (58%) (Mahmood & Gheewala, 2020).

The transport process of biomass fuel can be measured in terms of ton-kilometers (tkm), which is a unit used to express the amount of weight transported over a certain distance. For instance, one ton-kilometer represents the transport of one ton of weight over one kilometer. In the context of this situation, 1 ton of biomass fuel is being transported over 7 kilometers for a single trip. Therefore, the transportation distance for a round trip taken is 14 tkm. It is crucial to accurately measure the distance and weight of the biomass fuel being transported.

Coal Transportation

Apart from RS transportation, coal transportation was also required for the S2. The coal requirement as per the functional unit was also calculated simply by assuming the calorific value for coal 45 MJ/Kg. So the coal required in comparison to 1ton of RS to generate same amount of energy was 311.1kg. The coal transportation was considered to be from the Thar coal site to Gujranwala as we assumed our RS powerplant to be in Gujranwala. The transportation distance was calculated as 840 tkm for a round trip.

3.3.3 The annual requirement for rice straw

To determine the necessary amount of biomass fuel needed for a year, an estimation is made based on the heating value of the available biomass. This annual biomass requirement is not a fixed quantity, as it can be influenced by system efficiency. This variable plays a pivotal role in evaluating the amount of biomass fuel required to meet a given system's heating needs. Therefore, the estimated annual biomass requirement will fluctuate based on the overall efficiency of the system.

The annual biomass demand (M) in tons is calculated the by equation 2 presented below (Uzair et al., 2020).

Annual Feed RS Requirement

$$M = \frac{Pc \times 3600 \times OH}{LHV \times \eta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \; Eq\ 2.$$

M = Amount of straw in tons required to annually feed the powerplant of 10MW.

Pc = Plant capacity in MW (10).

LHV = Lower heating value of the fuel burned to produce electricity 14 MJ/kg. (Shafie et al., 2014)

OH = Operating hours that the plant will run annually 8400h

η = Powerplant efficiency to convert thermal energy to electrical energy. Assuming an efficiency of 20% (Suramaythangkoor & Gheewala, 2010).

After calculating annual straw demand that value was used in equation 1 to find the distance to be traveled to transport baled straw to the powerplant.

3.4 Rice Straw Open Burning (S1)

Rice straw open burning (*OB*) is the base case scenario and normal practice to get rid of the rice straw after the rice harvesting season. So, the impacts of rice straw open burning will be here calculated based on the emissions factors taken from the (Andreae & Merlet, 2001) as the emission factors of agriculture residue burning. S1 only discusses the open burning of RS.

3.5 RS Direct Combustion and Offset Coal Based Energy Impacts (S2)

The direct combustion technology for biomass involves feeding raw biomass material into a steam boiler which produces super-heated steam then drives a steam turbine and generator and eventually generates electricity. This is a well-established conversion technology. However, data sources for power generation using rice straw were limited in SimaPro, most data is cited from the studies conducted by different researchers on this technology (Chen et al., 2020; Mahmood & Gheewala, 2020; Uzair et al., 2020; Żołądek et al., 2021). Compared to other thermo-chemical conversions, energy production from the direct combustion of RS (*ERs*) offers high energy efficiency (Moliner et al., 2020). Moreover, Residual biomass provides the most environmentally friendly option, as it dually benefitted by avoiding emissions from biowaste management and energy crop production (Prasad et al., 2020).

The annual straw demand of the power plant is approximately 108,000 tons with a net output of 777.77 kWh per ton of combusted rice straw in the boiler.

The net output is calculated by equation 3.

$E_{output} = f \times \mu \times \eta$ ……………………*Eq 3*

Where

E_{output} = Electricity in kWh

f = Feedstock burned in the boiler in kg

μ = Calorific value in kWh/kg

η = Power plant efficiency

Besides straw, the operation of steam-based power plants mainly relies on water as a natural resource. These power plants require water for their boiler and cooling tower systems. An estimated 3.238 m^3/ton RS of deionized water is needed for cooling purposes to power a powerplant to avoid problems like scaling and slag formation and 216.6 liters is required as boilers makeup and to compensate evaporation losses (Anna Delgado Martin et al., 2012). Deionized water is very close to distilled water as in the SimaPro this was the best-suited option among the choices. The water and steam flow in the boiler and turbine occurs in a loop, with evaporation losses occurring at the cooling tower (Sugathapala, 2022). Hence, to generate electricity of 777.77 kWh the amount of water requirement is 3.49 m^3. Coal-based electricity (*Eco*) is the main source of electricity in most developing and even developed countries. So the amount of coal that required to produce the same amount of electricity as from the 1 ton of RS is 311 kg by assuming the calorific value of 45MJ/kg. The coal is assumed to be transported from Thar to Gujranwala. While the rest of the data for *ECo* was taken from the Ecoinvent data.

3.6 Direct Combustion of RS & Substitute Grid Electricity of Pakistan (S3)

According to (Mahmood & Gheewala, 2020) the agriculture and energy sectors of Pakistan collectively account for 90% of total GHG emissions, and 43.5% are mainly caused by the field burning of agricultural biomass, agricultural soil, and rice cultivation remaining 46.5% are from the energy production sector (industries, transport, and fugitive fuel emissions). The grid electricity (*EGr*) of Pakistan mainly comprises non-renewable energy sources and is majorly contributed by fuels like Regasified liquefied natural gas, coal, gas, and residue fuel oil (PES 21-22). So, as per the study objectives, S3 aims to calculate the offset environmental impacts if the grid mix electricity of Pakistan is replaced with electricity from rice straw.

3.7 Briquette Production and Offset Wood Combustion Impacts (S4)

The process of creating briquette fuel (BF) from RS also involves collection and transportation processes followed by pre-treatment step of chopping and at the end briquette formation. Drying is not considered here as it is already mentioned that RS is sundried and has a moisture content of 10-15% (Shafie et al., 2014). The chopped RS is then fed into a briquette formation machine that forms it into briquettes through high pressure. Briquette fuel formation energy requirements are majorly in the form of electricity during the chopping of RS and briquetting stage. After briquette formation, the travel distance for briquette collection is assumed as 30tkm. Then briquettes are set to be burned in the three brick stoves as replacement of wood open burning (*WOB*) for energy or cooking purposes. The impacts of these are discussed in the result and discussion section.

3.8 Life Cycle Impact Assessment (LCIA)

In the current study, CML-IA baseline methodology was selected to assess different environmental factors involving the potential for abiotic depletion of resources and fossil fuels, Global warming (GWP-100) as well as Freshwater aquatic ecotoxicity potential, Ozone layer depletion potential, Human toxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, Photochemical oxidation potential, acidification potential, and eutrophication potential. The abiotic depletion potential is an emission category for evaluating the environmental effects that arise from the extraction and usage of nonrenewable resources, such as minerals and fossil fuels, which are expected to be depleted in the future. This category has long-term implications, as it reflects the deficiency of resources while limiting their availability to the next generations. The Acidification Potential is another category used to measure environmental impacts. This considers the adverse impacts of SO_2 and NO_x on water resources, soil, ecosystems, and living beings. Eutrophication evaluates the nitrogen and phosphorus accretion as nutrients in the environment, leading to the rapid growth of underwater vegetation. The Global Warming Potential, simply written as (GWP-100) measures the GHG contribution towards the greenhouse effect which ultimately results in climate change over 100 years. The ozone Layer Depletion category evaluates the impacts of chlorofluorocarbon (CFC) emission into the atmosphere. Which eventually depletes the stratospheric ozone layer, which acts as a shield against UV rays. Human toxicity evaluates the harmful impacts of non-biodegradable substances accumulating into living species. Exposure to such substances can occur through inhalation or ingestion. The deleterious impacts of anthropogenic formation from different photochemical reactions are evaluated in photochemical oxidation potential. This ozone formation mainly resulted from the photochemical reaction between NMVOC and NO_x (Freitas et al., 2022). The CML-baseline method, which is incorporated into SimaPro software, was selected to calculate all the midpoint indicators. The simulation and calculation of the system were performed using SimaPro software, which provides access to a comprehensive library and different methods(Nguyen et al., 2016). To calculate the net impact avoided these three equations 4,5 and 6 are used for S2, S3 and S4 respectively.

$ERs - OB - ECo$ ………………*Eq. 4*

Where:

ERs = Electricity from RS

OB = Open burning of RS

ECo = Electricity from Coal

$ERs - OB - EGr$ ………………*Eq. 5*

Where:

ERs = Electricity from RS

OB = Open burning of RS

EGr = Grid mix electricity

$BF - OB - WOB$ ………………*Eq. 6*

Where:

BF = RS Briquette burning

OB = Open burning of RS

WOB = Wood open burning

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

LCA methodology was adopted to evaluate and compare the environmental performance of all scenarios for RS utilization by converting their impacts into midpoint indicators using the CML baseline method. The results obtained from this study advocate sustainable RS utilization for bioenergy production while providing alternatives for the open burning of crop residue. The findings highlight the potential for RS to be managed in an eco-friendly manner, while also providing a renewable source of energy. This LCA could provide significant implications for policymakers, businessmen, and individuals seeking to adopt more sustainable practices in their use of RS. All the results are discussed according to the functional unit of 1 ton. The GHG emissions for S1, S2, S3 and S4 are 1590.6, -1776, -370 and -1461.89 kg CO_2 equivalents respectively. The negative sign with the values shows the carbon emission saving by utilizing rice straw for bioenergy. Hence, one can save these carbon emissions by sustainably utilizing rice straw. The reduction values are 1776, 370 and 1462 kg CO_2 equivalents for S2, S3 and S4 respectively. The overall net reduction for GHGs was high (1776 kg CO_2 equivalents) observed in the case of electricity generation from rice straw by direct combustion technology and replacing this with electricity from coal power plants. Here the table 4.1 shows the impacts of each midpoint indicator.

Table 4.1. LCA results against all midpoint indicators based on the CML method for all 4 scenarios.

Impact category	Unit	S1 *(OB)*	S2 *(ERs-OB-ECo)*	S3 *(ERs-OB-EGr)*	S4 *(BF-OB-WOB)*
Abiotic depletion	kg Sb eq	0	-0.00483	-0.00033	0.00044
Abiotic depletion (fossil fuels)	MJ	0	-27815.7	-5198.5	825.4
Global warming (GWP100a)	kg CO_2 eq	1590.6	-1776.0	-370.0	-1461.8

Ozone layer depletion (ODP)	kg CFC-11 eq	0	-0.000153	-0.0000310	0.00001
Human toxicity	kg 1,4-DB eq	484.3	-1414.9	-565.2	-1742.81
Fresh water aquatic ecotox.	kg 1,4-DB eq	104.99	-890.55	-169.24	15.30
Marine aquatic ecotoxicity	kg 1,4-DB eq	104.16	-2906383.17	-203225.96	-35940.15
Terrestrial ecotoxicity	kg 1,4-DB eq	4.25	-6.39	-4.91	-13.55
Photochemical oxidation	kg C2H4 eq	7.40	-7.7	-7.38	-2.39
Acidification	kg SO_2 eq	1.73	-12.94	-2.36	-0.68
Eutrophication	kg PO4--- eq	0.32	-3.76	-0.22	-0.51

4.2 Life Cycle Impacts Assessment Results

4.2.1 Global warming potential (GWP-100)

GWP-100 represents the relative impacts of GHGs emissions over a time of 100 years, which are measured quantitatively (Alengebawy et al., 2022; Fawzy et al., 2020). This is the main midpoint indicator that shows the contribution of a process towards climate change which is the major problem that Earth is facing, its effects are not only limited to humans although every creation on this planet is bearing the brunt of its consequences. The table 4.2 showing the GWP impacts of all processes that are under consideration during research. Open burning of rice straw in the field showing the potential of 1590 kg CO_2 eq. emissions and these emissions mainly lead to the global warming potential. Apart from that the CO_2 emissions from open burning the direct combustion technology emit more CO_2 relatively since the direct combustion technology involves the primary stages of raking, baling, loading and transportation after that actual process starts for electricity production. Electricity from coal emits the highest amount of CO_2 in comparison to all the technologies because coal has more carbon content and different calorific values. Although the table 4.2 clearly shows the contribution of each technology or fuel to GWP in kg CO_2 equivalent.

Table 4.2. Global Warming Potential from all technologies

OB(RS open burning)	*ECo(Electricity from Coal)*	*ERs(Electricity from RS)*	*EGr(Grid Electricity)*	*BF(Briquette fuel combustion)*	*WOB(Wood open burning)*
1590.6	1802.1	1616.7	396.1	1606.3	1477.7

The net reduction of GHG emission in graphical representation is shown in figure 4.1.

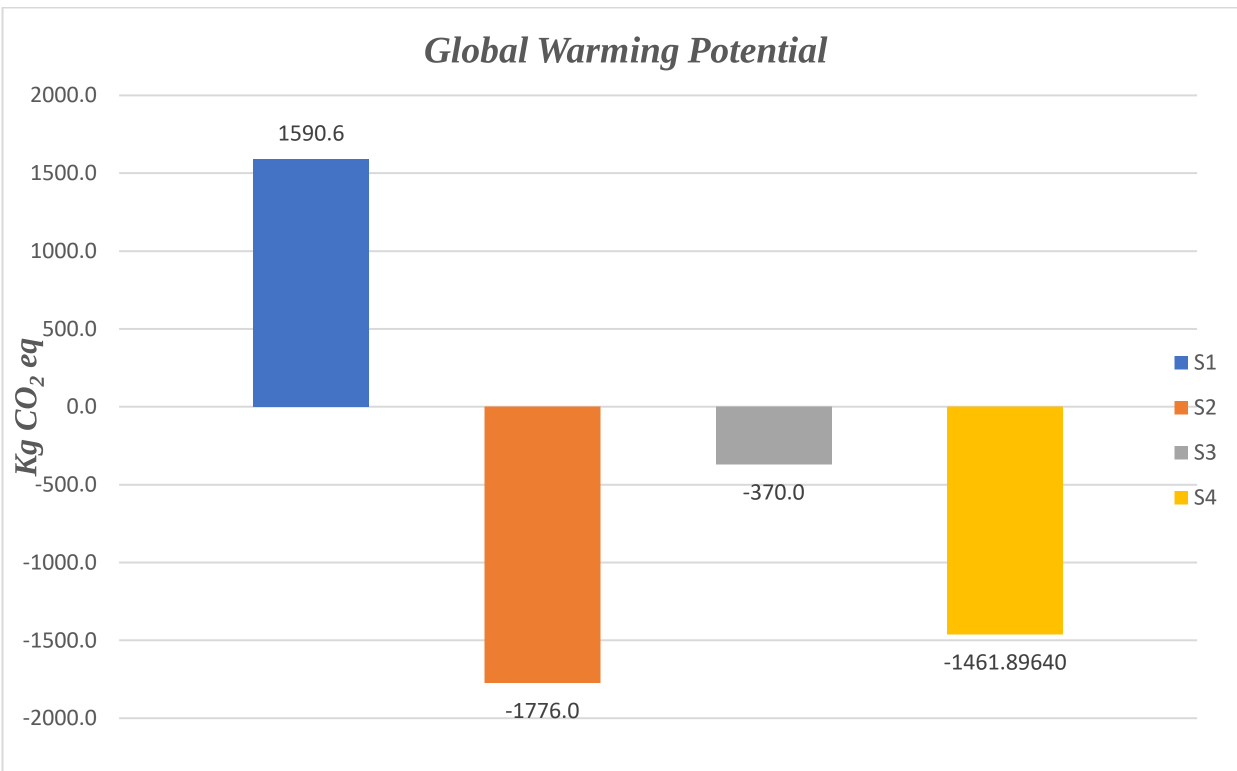

Figure 4.1. GHG emission calculation of all scenarios

When compared to an ordinary grid mix power and electricity derived from coal, electricity produced from rice straw has a reduced emission footprint. This indicates that compared to burning coal or using the typical energy mix from the grid, burning rice straw for electricity produces fewer greenhouse gases per unit of electricity produced. The scenarios reduce emissions from these higher-emission sources by substituting rice straw-based electricity for coal-based electricity (S2) and grid mix electricity (S3). Since rice straw is a renewable resource and emit less CO_2 than coal, substituting it significantly reduces greenhouse gas emissions. This is quite emphasizing that similar amount of electricity is produced from the 1 ton rice straw and in comparison to coal which is producing 777.77 kWh of electricity from the 311 kg of coal. The amount of GWP is quite high in term of per unit quantity of electricity produced. 1 kWh electricity from coal emit 2.31 kg CO_2 eq. GHG, while electricity from RS emit 2.07 kg CO_2 eq. Moreover, rice straw combustion has closed carbon cycle as compared to coal making the net increase in atmospheric CO_2 less as compared to coal. Apart from CO_2 there are other GHG which contribute to global warming using RS for energy also helps to reduce other GHG emissions and environmental impacts from coal mining and other processes. The rice straw can be managed this way sustainably rather than open burning without harnessing the energy from it. So, RS has the potential to replace coal for meeting energy needs.

Although it makes up a smaller portion than pure coal, fossil fuel-based power is still a major component of Pakistan's grid mix electricity. Even if rice straw-based electricity is used in place of coal based and grid mix electricity, the GHG emission can be reduced and is a more sustainable option than these conventional sources of electricity.

4.2.2 Abiotic depletion

The measure of abiotic depletion, which is reported in units of kg Sb equivalent, denotes the scarcity of non-renewable resources such as fossil fuels and particularly deals with resources like minerals and clay. This impact category is used to evaluate the environmental impact of the usage and mining of natural resources, which are non-renewable and likely to be depleted over time. This midpoint indicator is particularly significant due to its future implications, as the depletion of mineral resources and limited options for future generations will inevitably have an impact. The assessment of abiotic depletion is critical for identifying sustainable practices that prioritize resource conservation and seek to minimize their negative impact on the environment.(Freitas et al., 2022; Osman et al., 2021).

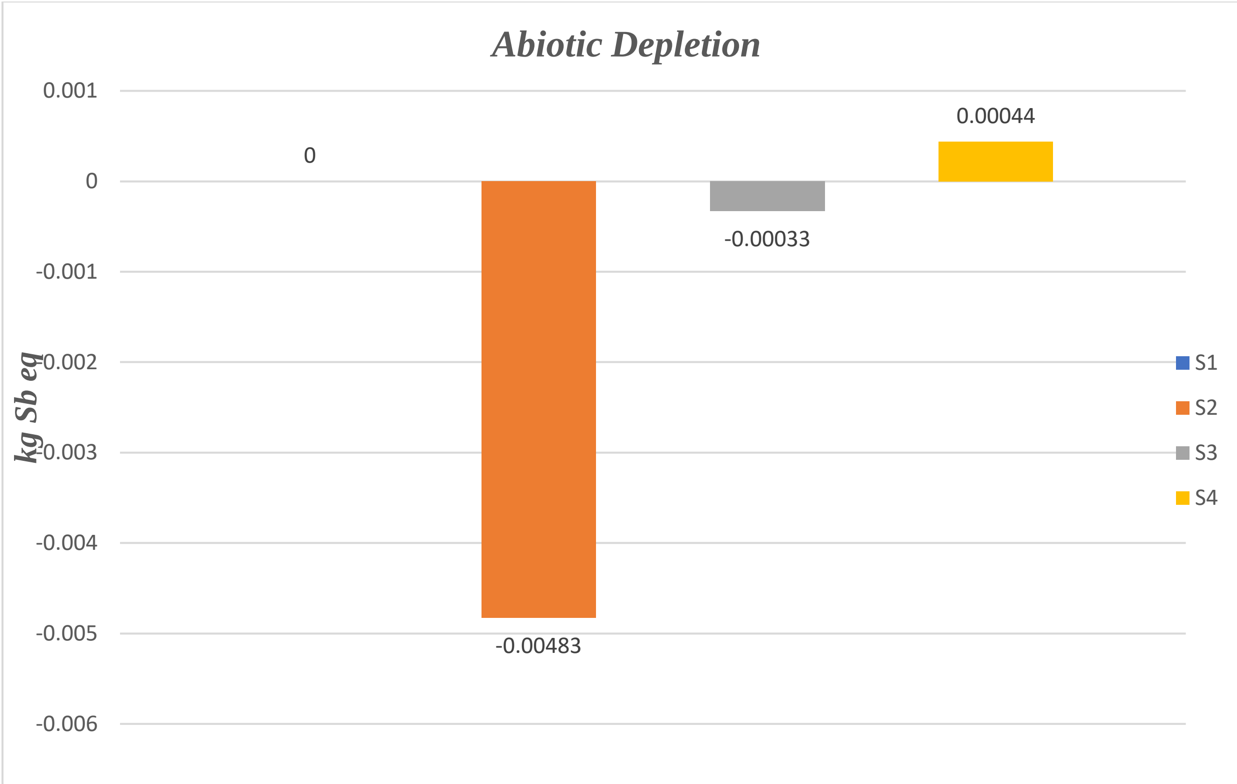

Figure 4.2. Abiotic depletion potential

In S1, the abiotic resource depletion potential (ADP) was not detected while the values for the direct combustion, Pakistan grid mix, and briquette formation were considerably low toward resource depletion (Alengebawy et al., 2022). The primary cause of the decline in the abiotic depletion potential trend for S2 and S3 in contrast to S1 and S4 is the replacement of non-renewable energy sources. Coal mining and combustion are highly depleted, abiotic resource processes due to the extraction and processing of non-renewable resources. The extraction and processing of non-renewable resources, coal mining and combustion, severely depletes abiotic resources. Since rice straw is a byproduct of agriculture, using it to produce power requires little extraction of abiotic resources. Fossil fuels, which have a greater ADP than other energy sources, are part of Pakistan's grid mix electricity. By substituting energy derived from rice straw for a portion of this grid mix, the overall ADP is decreased by reducing reliance on fossil fuels. The value for S4 is still positive due to processes like baling and briquetting having the highest contribution towards resource depletion in S4. However, this impact is negligible. The identification of depletion potential is crucial for evaluating the sustainability of resource use and implementing measures to minimize the negative effects on the environment.

4.2.3 Abiotic depletion potential (fossil fuels)

Like abiotic depletion potential, this is similar to the depletion of natural non-renewable energy resources, particularly fossil fuels and it is expressed in terms of the energy unit of MJ. Upon closer examination, this graph presents a similar picture to the one above. The main difference between abiotic depletion fossil and abiotic depletion is that this indicator is measured in terms of energy unit.

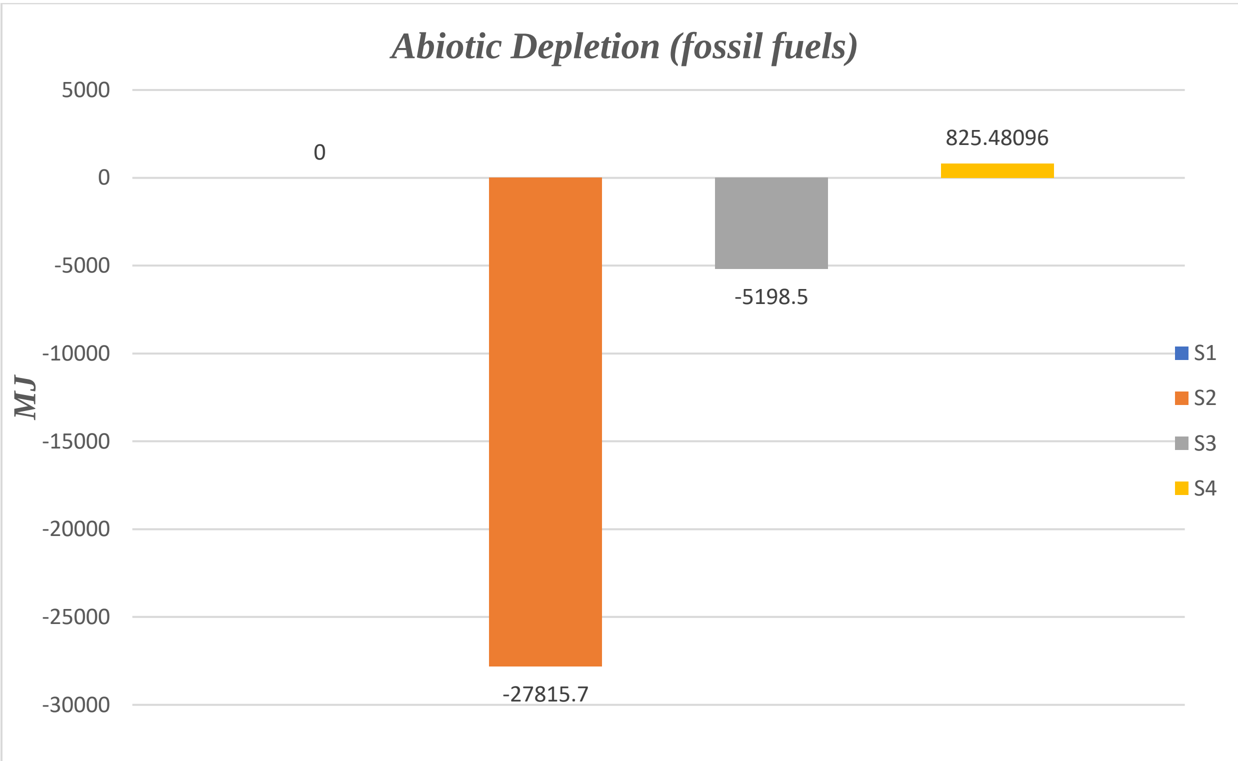

Figure 4.3. Abiotic depletion potential (fossil fuels)

4.2.4 Ozone layer depletion (ODP)

The negative impact of CFC regarding impacts on the environment and ozone layer depletion is considered in this midpoint indicator. This indicator is measured in kg CFC-11 eq. In summary, S2 and S3 avoid contributing to ozone layer depletion due to the less emission of ozone-depleting substances associated with rice straw-based electricity production compared to coal and grid mix electricity. In contrast, the briquette formation process in S4 increases the use of materials or processes that contribute to ODP, resulting in a minor positive impact on ozone layer depletion, briquette formation involves energy consumption in the form of diesel and electricity, against the assumed no energy consumption in case of wood burning. Even though S4 demonstrated positive values, this value was significantly lower and remained below the reference value of CFC-11 which is 1.0. The negative signs in S2 and S3 indicate that these scenarios lower CFC emissions. (Alengebawy et al., 2022).

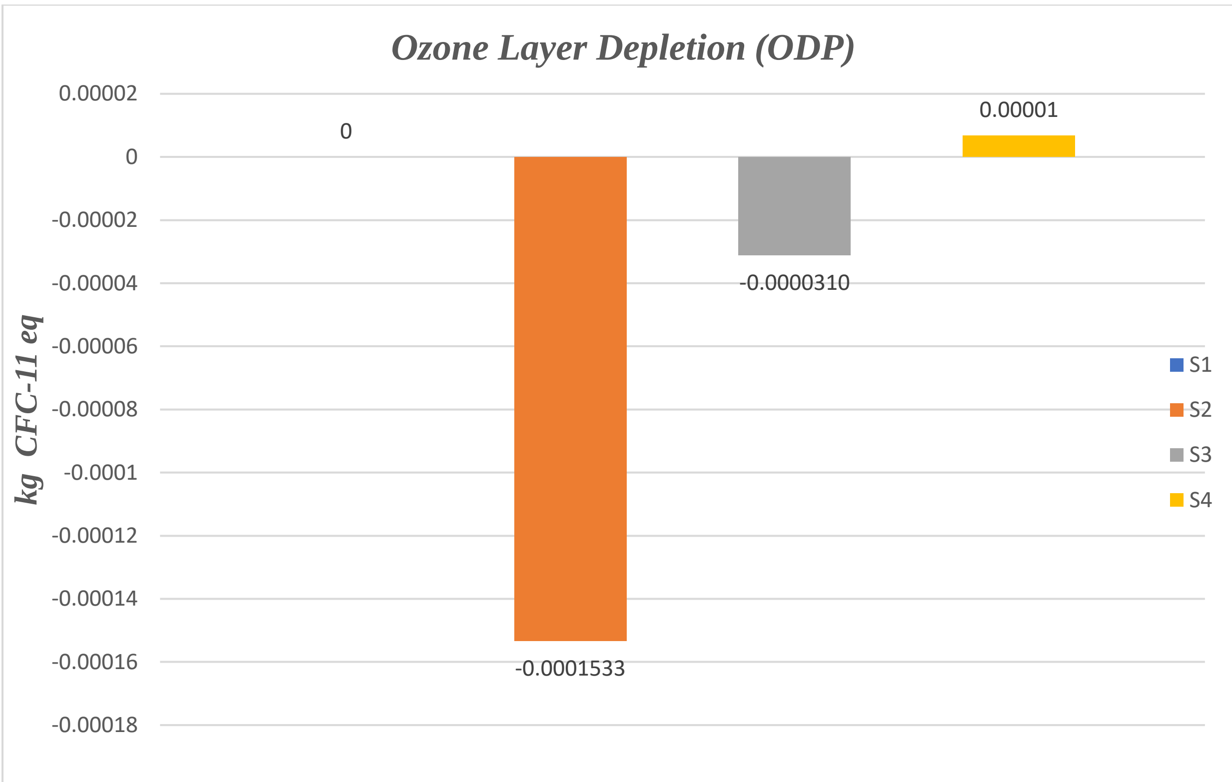

Figure 4.4. Ozone layer depletion potential

4.2.5 Human Toxicity

The human toxicity measurement unit is 1,4 dichlorobenzene equivalents. The human toxicity index can be varied as carcinogenic and non-carcinogenic. Carcinogenic is based on the potential harm from cancer-causing chemicals while the non-carcinogenic index is the dangers associated with exposure to non-carcinogenic chemicals released into the environment (Osman et al., 2021). However, human toxicity is mainly caused by emissions related to NO_X, SO_2 chromium VI, benzene, hexachlorobenzene, and arsenic. (Alengebawy et al., 2022; Corsten et al., 2013). S4 demonstrates the highest reduction in human toxicity because natural wood, when burned openly, emits significant amounts of NOx and SO_2 due to incomplete combustion; this issue can be mitigated by substituting wood with rice straw briquettes. Similarly, S2 addresses major contributors such as arsenic, chromium, NOx, and sulfur dioxide, which are emitted in large quantities into the air or remain in ash from coal combustion. By replacing coal-based electricity with the sustainable option of electricity from rice straw, these emissions can be avoided, as is also the case for the other scenarios. The trend in human toxicity across all four scenarios is as follows: S1 > S3 > S2 > S4.

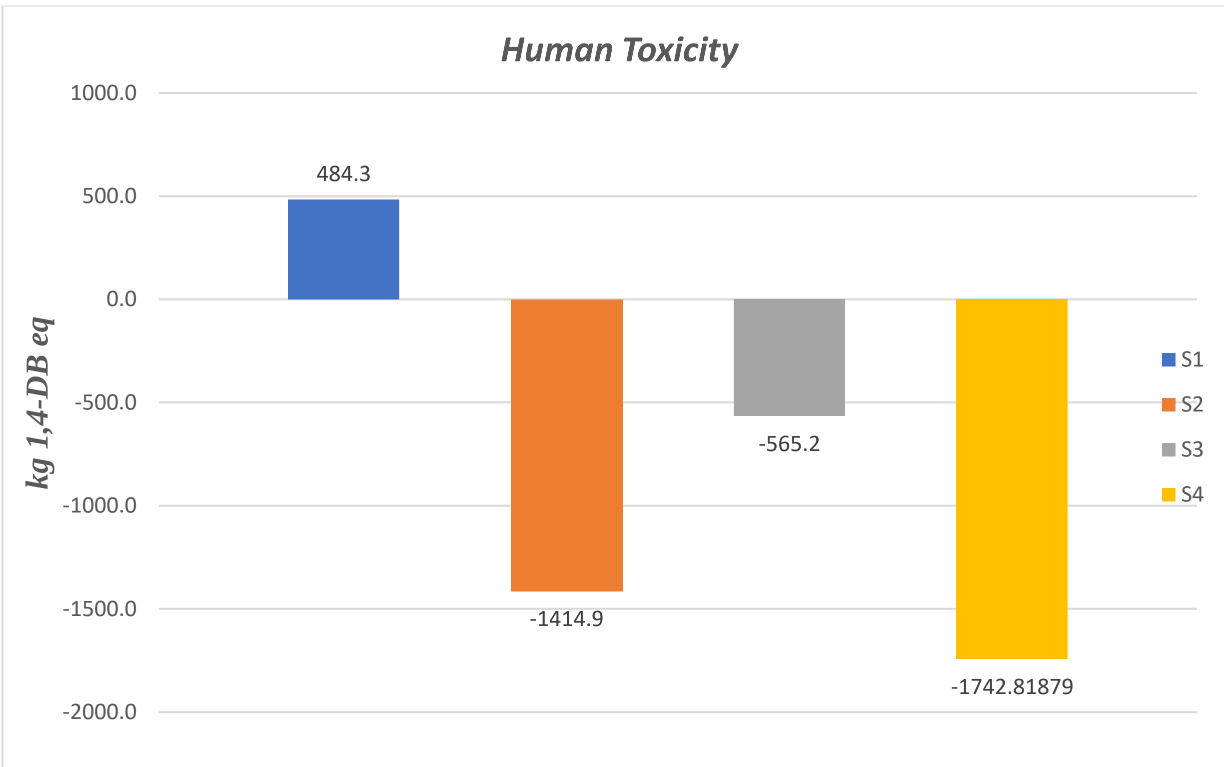

Figure 4.5. Human Toxicity Potential

4.2.6 Acidification

Acidification potential is mainly caused by SO_2, NO_X, HCL, and HF and this expressed in kg SO_2 eq. (Shafie et al., 2014). When we use RS for electricity production and replace electricity generated from RS by electricity from coal or other fossil fuels like petrol, diesel, or natural gas—major components of the Pakistani grid mix, less NOx and SO_2 will be emitted in comparison to energy from the fossil fuels. This means there are fewer chances of sulfuric and nitric acid formation, thereby avoiding acidification. Coal combustion is a significant source of NOx and SO_2 emissions, so replacing it with sustainable option yields positive outcomes. This is why S2 shows the highest acidification reduction potential, followed by S3 and S4.

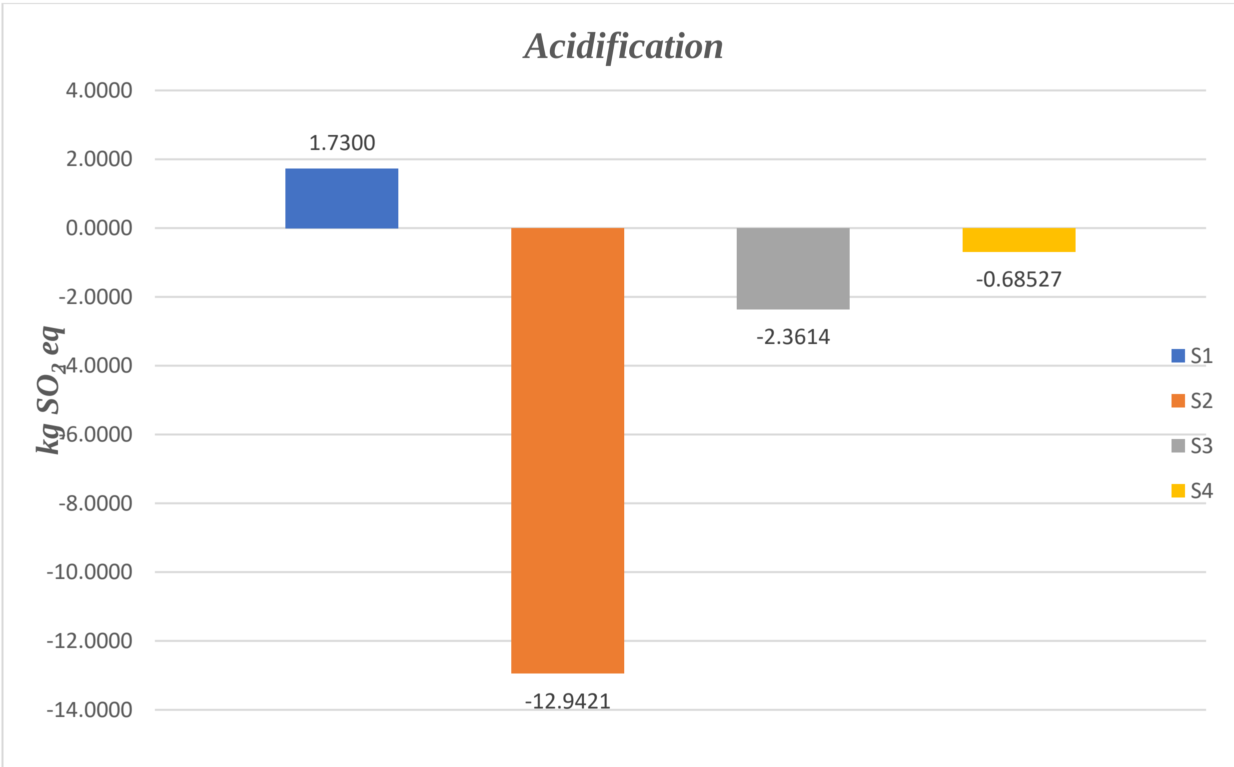

Figure 4.6. Acidification potential

Acidification for S1 is approximately 1.7 kg SO_2 eq. This is the only indicator that is positive compared to the other scenarios. This is due to the open burning of rice straw, which releases toxic gases that react in the atmosphere to form acids, leading to acid rain and potential acidification. However, this issue can be avoided by sustainably utilizing this biowaste.

4.2.7 Eutrophication

Releasing excessive nutrient amount is known as eutrophication which is reported as kg PO_4^{3-} equivalents (Osman et al., 2021). Eutrophication is mainly caused by phosphate PO_4

$^{3-}$, nitrogen oxides NO_X, nitrates NO_3, and ammonia NH_3 (Shafie et al., 2014). Utilizing straw has a significant benefit in preventing the open burning of straw, The eutrophication potential is primarily caused by the addition of ammonia, nitrogen, and phosphorus to water bodies through the hydrological cycle. By emitting less NOx, phosphorus, and ammonia, this impact can be controlled. S1, and S3, show positive trends, with S2 avoiding the highest eutrophication potential and Scenario 3 showing the lowest. The eutrophication value in S3 also reduced since Pakistan's grid energy mix mainly comes from non-renewable energy sources, and it requires mining for the extraction of fossil fuels. According to (Gaete-Morales et al., 2019) mining activities account for the discharge of considerable quantities of phosphate into freshwater systems. Moreover, the combustion of fossil fuels for grid electricity and the burning of rice straw in S3 also emit nitrates, ammonia, and phosphates in the form of flue gases. These substances enter hydrological cycles through cooling water, ultimately resulting in eutrophication. The reducing trend for this indicator is as S2<S4<S3<S1.

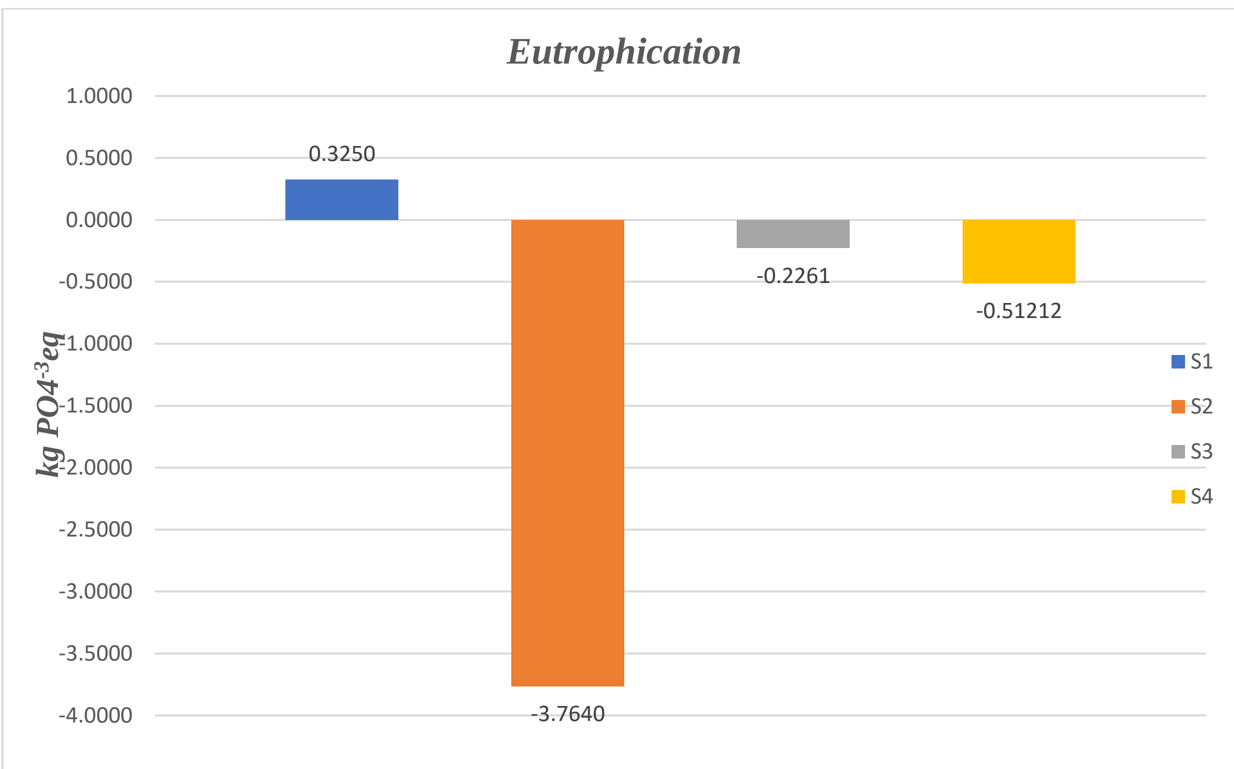

Figure 4.7. Eutrophication Potential

4.2.8 Photochemical oxidation potential (PCOP)

The consequences subjected to affect our ecosystem and human health due to the emission of reactive substances are mostly related to PCOP and these are measured in kg ethene (C_2H_4) equivalent (Osman et al., 2021). Moreover, the PCOP is mainly caused by the emission of NO_X, CH_4, CO, and particulate matter that ultimately results in ozone formation (Soam et al., 2017). Burning coal, rice straw, and wood emits NOx, SO_2, PM, and VOCs. When these pollutants react with sunlight in the presence of photochemical reactions, they produce secondary pollutants such as ozone and acid rain. Moreover, ozone is a primary precursor of smog. This photochemical oxidation potential can be reduced by emitting fewer pollutants. Therefore, generating electricity through the direct combustion of rice straw and replacing coal-based electricity, along with Pakistan's grid mix electricity, yields positive results, as shown in the graph. The highest reduction in photochemical oxidation potential is observed in S2, followed by S3 and S4.

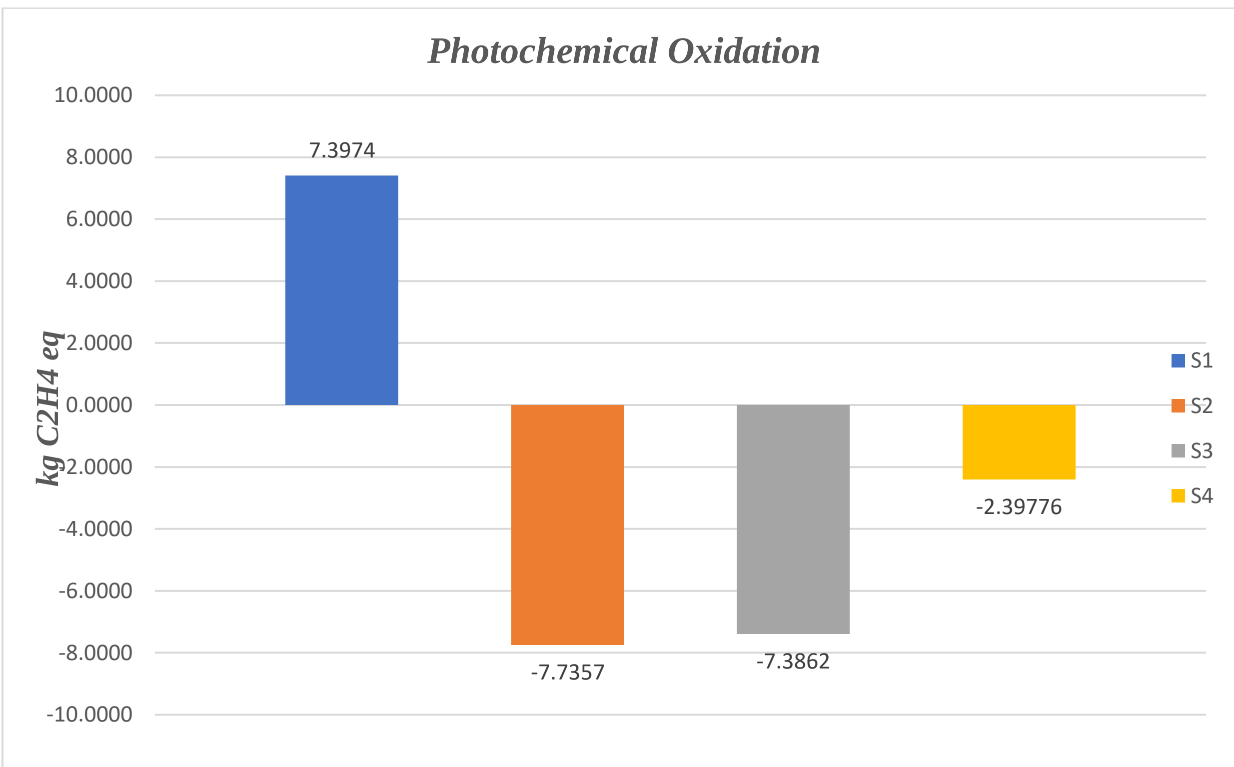

Figure 4.8. Photochemical oxidation potential

4.2.9 Freshwater Aquatic Ecotoxicity

Freshwater ecotoxicity is commonly caused by vanadium and measured in kg 1,4-DB equivalents whereas other emissions that can cause freshwater toxicity are nickel, beryllium, chromium VI, arsenic, and Mercury (Corsten et al., 2013).

Freshwater aquatic ecotoxicity is reduced in both scenarios S2 and S3, with S2 having the most beneficial effect. S4 indicates a small negative impact in comparison to S1 by contributing somewhat to freshwater aquatic ecotoxicity. This is less than the worst-case situation, though. In S2 and S3, the negative values indicate a reduction in compounds that induce freshwater aquatic ecotoxicity, which is positive.

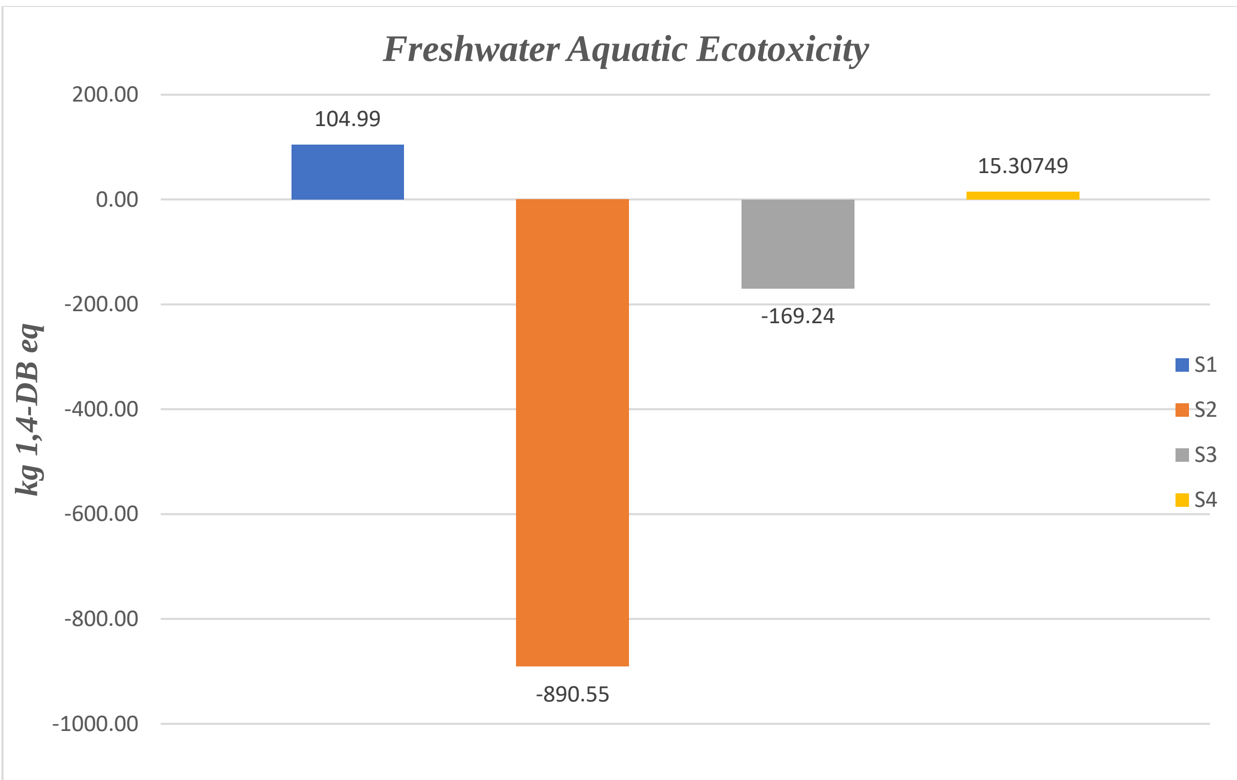

Figure 4.9. Freshwater aquatic ecotoxicity potential

4.2.10 Marine Aquatic Ecotoxicity

Similar to freshwater ecotoxicity marine aquatic ecotoxicity evaluates the impacts of toxic substances on marine life. This indicator is also measured in the same unit as the previous one. Commonly caused by vanadium and measured in kg 1,4-DB equivalents marine aquatic ecotoxicity has impacts on marine life.

Burning wood, coal, and rice straw in the open can release persistent organic pollutants like furans and dioxins and heavy metals such as arsenic, lead, mercury, and chromium into the atmosphere. Additionally, the emissions of PM, SO_2, and NOx from burning these fuels can react with atmospheric water to produce acid rain, which corrodes aquatic bodies and endangers marine life. Replacing fossil fuels with rice straw energy production is a sustainable way to avoid this. The graph clearly illustrates the favorable result, with S2 having the largest decrease in marine ecotoxicity, followed by S3 and S4.

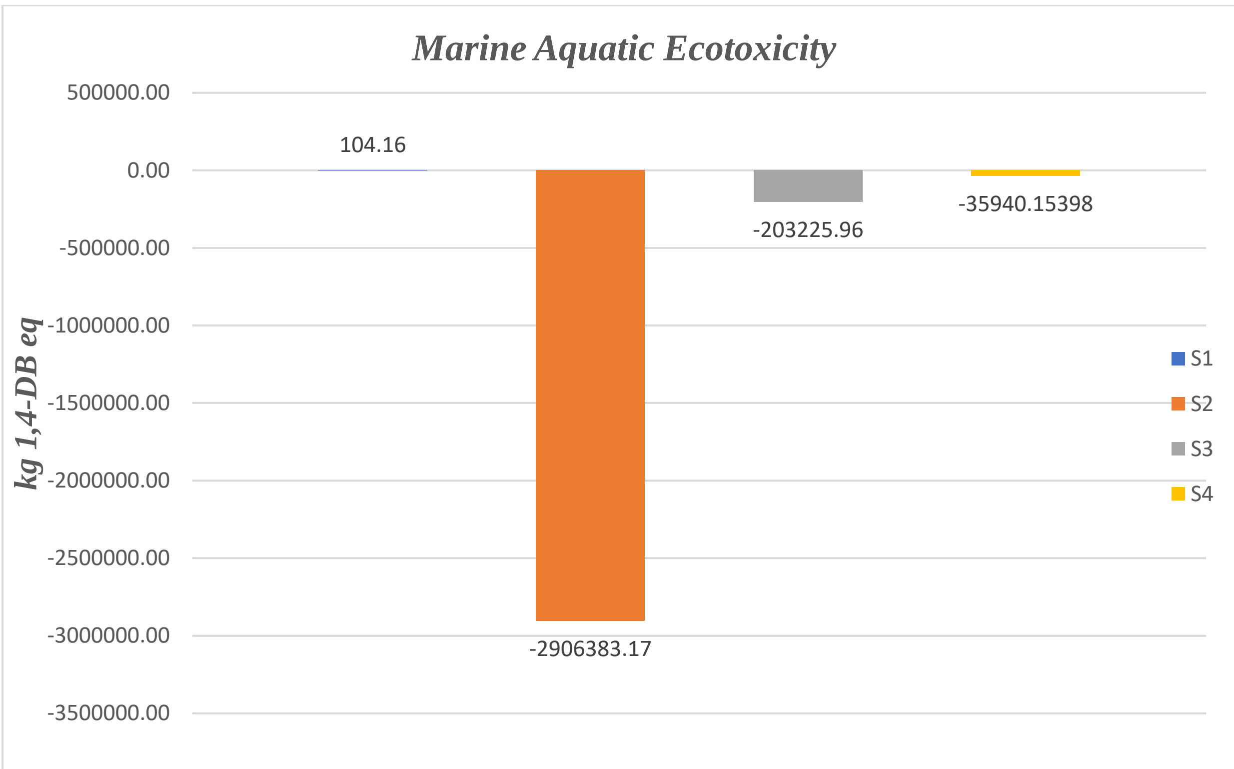

Figure 4.10. Marine aquatic ecotoxicity potential

4.2.11 Terrestrial Ecotoxicity Potential

This indicator examines the long-term emission effects of harmful chemicals, primarily arsenic, chromium IV, vanadium, and mercury, on the terrestrial environment across an indefinite time horizon.

Pollutants and heavy metals that cause terrestrial ecotoxicity can build up in the soil, plants, and animals. This goes along the same route as the indicator that came before it. Because wood and coal have different structures, avoiding wood burning reduces terrestrial ecotoxicity to the greatest extent possible. This indicates that the most environmentally friendly solution for avoiding terrestrial ecotoxicity is to replace wood with briquettes made of rice straw.

It is evident that S4 has the highest reduction in terrestrial ecotoxicity, as it avoids chromium and other long-term emissions that contribute to terrestrial ecotoxicity. The reduction in this indicator is ranked as follows: S4 > S2 > S3 > S1.

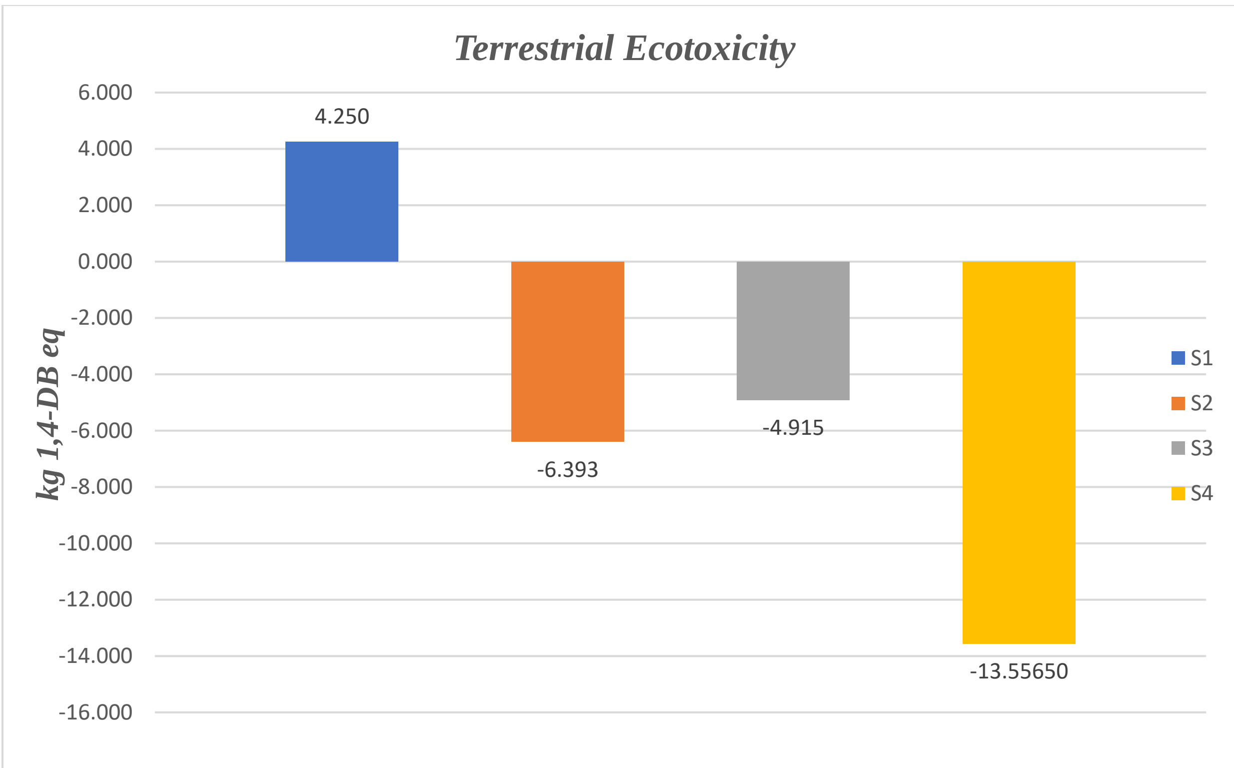

Figure 4.11. Terrestrial ecotoxicity potential

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

A life cycle assessment was conducted to evaluate the impacts of one business as usual (open burning) and 3 proposed alternative scenarios for utilizing rice straw efficiently and sustainably. The three proposed scenarios show the positive impacts of utilizing straw for electricity production and replacing coal-based and Pakistan grid-mix electricity. The last scenario also highlights the potential positive impacts of using rice straw for briquette formation replacing wood burning in the three-brick stoves in rural areas where there is no access to natural gas.

Electricity from the direct combustion of rice straw contributes 2.07 kg CO_2 eq/kWh, while the open burning of rice straw contributes 1.5 kg CO_2 with a reference emission factor of 1569 g/kg (Andreae & Merlet, 2001). Electricity generation from coal contributes 2.31 kg CO_2 eq per kWh of electricity. The emission of GHG can be reduced by 1.82 kg CO_2 eq per kWh of electricity generation in comparison to coal. The higher emissions from direct combustion compared to open burning are due to the processes involved, such as raking, baling, loading, and transportation of straw. However, the emission factor for open burning and direct combustion assumed to be the same. The complete LCA findings show that S2 is the most environmentally friendly scenario. Coal is the potential source of electricity in most of the developing countries around the globe. Coal has more deleterious impacts in term of climate change than any other fuel due to the rich concentration of carbon in the coal. However, the highest emission reduction was noted in the marine aquatic ecotoxicity potential reducing this potential by -2906383.17kg 1,4-DB-eq in S2. The S2 has a significantly beneficial contribution towards the reduction of photochemical oxidation, global warming, eutrophication, and acidification potential. All scenarios showed varying results, however, all showed a more favorable environmental performance than the in-situ burning of straw. Moreover, the practical implementation of such biomass plants is a dire need in Pakistan where cheap and clean energy can play its role in the economic development of the country. Eventually, crop residues are a valuable resource that can be used for energy generation in a way that helps to avoid environmental pollution and health issues. To assess the ecological, social, and economic sustainability impacts of energy generation from crop residues, LCA approach is recommended. As there are multiple pathways for generating energy from agricultural residues, LCA can be utilized to identify the most suitable type and route among different technologies and processes that are currently running based on the specific feedstock and location. Researchers should thoroughly investigate alternative methods for the utilization of rice straw in bioenergy generation and its incorporation into soil as a means of enhancing soil fertility. The comprehensive exploration of rice straw and other biomass utilization holds the potential to not only enable farmers to generate income through biomass sales but also to mitigate the detrimental environmental consequences associated with the widespread practice of open burning of rice straw in agricultural fields.

5.2 Recommendations

The recommendation for the other researchers is this study only assess the environmental impacts of the discussed scenario. However, economic and social life cycle assessment is also recommended to assess the economic cost and social factors to be considered while establishing such energy generation powerplants. Moreover, there are many other energy conversions technologies for bioenergy production from rice straw or other agricultural waste like pyrolysis, anaerobic digestion these processes can be taken into account to assess the environmental viability of these options.

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