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Original scientific paper

Environmental Value Measurement and Potential Economic Impact Analysis of Biomass Energy Projects

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Abstract: This paper explores the co-incineration of biomass pellets and sewage sludge, which is looking at the environmental effects, energy recovery, and pollution creation. The principal objectives are to clarify how to use the co-incineration energy and assess how released contaminants affect the environment. Five different blends are used in the co-incineration process, which takes place in a fluidized bed reactor with an average combustion temperature between 915 and 939 °C. The combustion process is defined by several monitoring methods, such as Fourier transform infrared spectroscopy, Continuous Mercury Monitoring Systems, thermocouples, and sensors for pressure and flow. The results show that harmful substance concentrations include namely SO_2 and NO_X, which have reached 12.39-1730.33 mg√m^{-3}N for SO_2 and 93.30-1156 mg√m^{-3}N for NO_X. In the worst-case scenario, SO_2 and NO_X emission limitations exceed 40 times and eight times, respectively. Regarding heat recovery, 5.35-7.69 MJkg^{-1} of potential energy can be recovered from flue gas. Heat recovery decreases as the fuel's sewage sludge content increases. Utilizing GaBi software for life cycle assessment, additional analysis of pollutant concentrations is possible. The results show that burning sewage sludge substantially affects climate change, land ecotoxicity, and human toxicity. The work offers a promising direction for additional research by suggesting that, under some circumstances, sewage sludge can be used as a supplementary fuel in massive combustion sources.

Keywords: biomass energy; climate change; economic analysis; environmental effects; pollution production

1 INTRODUCTION

The study aims to evaluate biomass energy projects' potential economic impact and environmental value. The main goal is to create reliable methods for measuring projects' positive environmental effects, such as carbon sequestration, greenhouse gas emission reductions, and overall ecological impact (Margallo et al., 2019). In addition, the study looks at the financial effects of biomass energy projects to do a comprehensive economic impact analysis. This entails assessing elements, which includes investments, running costs, employment generation, and the overall economic benefits to local and regional populations. The research contributes to the informed development and decision-making in the renewable energy sector by offering important insights, the twin dimensions of environmental sustainability and economic viability connected with biomass energy projects by a comprehensive approach.

Environmental issues in landfills include substantial land consumption and leachate discharge, which has adverse effects on groundwater. Fang et al., (2021) have incited an exploration of waste treatment approaches that are more environmentally sustainable. Incineration is identified as a feasible alternative due to its numerous benefits, including the eradication of organic matter and pathogens and a reduction in volume (Kolcava et al., 2019). Although widely used, the incineration of sewage sludge (SS) encounters significant challenges, most notably the energy required for moisture evaporation (up to 80 w.t.%). Furthermore, in comparison to alternative fuels, SS produces greater NOx emissions due to its increased nitrogen content (Y. Wang et al., 2019).

Research investigations include the one conducted by (Khan et al., 2022). The incineration properties of SS examined in pressurized bubbling fluidized-bed combustors. These studies uncover fluctuations in CO and N_2O concentrations dependent on temperature. The feasibility of incinerating moist and dried SS investigated and found that the energy-intensive drying process restricts the potential for incineration. An example of an alternative technology is the one that entails the mechanical dewatering and dehydrating of the pre-combustor. Numerous studies examining composite ratios with coal, biomass, leather, municipal solid waste, and paper mill sludge demonstrate that co-incineration is an increasingly viable alternative. The rationale is to reduce operational expenses, substitute primary fuels, and efficiently extract SS from landfills (Wu et al., 2020). Co-incineration is investigated in greater depth as an alternative method for efficiently harnessing the energy potential of sediment by a fluidized bed boiler.

The environmental impact assessment of biomass pellets (BP) and SS production is of the utmost importance in this context, given the findings of (Martínez et al., 2019). This suggests that while co-incineration maximizes energy recovery, it can be more expensive and contribute to the emission of pollutants. In contrast to studies with a limited scope, this research offers the comprehensive implications of a fraction substitution of the primary fuel with sewage sludge (Biswas et al., 2023). The research outlines the boundaries of co-incineration of sewage sediment, which emphasizes the difficulties associated with surpassing emission limits. This can have severe consequences for the environment and human health. The ash content growth of sewage sludge for fuel presents a notable challenge in ash management, primarily due to the substantially greater ash content found in sewage sludge than in biomass pellets.

The study makes a substantial scholarly contribution by comprehensively comprehending the intertwined aspects of economic feasibility and sustainability in biomass energy endeavors. By developing rigorous methodologies for quantifying environmental value, this study contributes to the wider academic conversation on renewable energy (Umar et al., 2020). It offers stakeholders a comprehensive evaluation of the ecological advantages linked to biomass projects. Furthermore, an economic impact analysis provides an essential additional dimension by illuminating these endeavors' financial viability and wider economic ramifications. The findings are poised to inform policymakers, investors, and industry professionals, facilitating more informed decision-making in the pursuit of sustainable and economically viable energy solutions (Twyford & Turner, 2023). This contribution is particularly pertinent in the current global context, where there is an increasing emphasis on transitioning towards renewable energy sources to address environmental concerns and promote economic resilience.

2 LITERATURE REVIEW

The extant body of literature concerning "Environmental Value Measurement and Potential Economic Impact Analysis of Biomass Energy Projects" highlights the complex interplay between economic viability and environmental sustainability of biomass energy. An essential aspect of this discussion revolves around quantifying the environmental advantages of biomass energy endeavors. Scholars consistently support the adoption of rigorous methodologies, and life cycle assessments (LCAs) have emerged as widely used instruments for exhaustive evaluations of the environmental impact linked to biomass energy generation. The emphasis above is demonstrated in the research conducted by (Baloch et al., 2021), which explicates significant benefits associated with biomass energy projects, including a substantial decrease in carbon emissions, improved land use efficiency, and a favorable influence on biodiversity conservation.

Concurrently, scholarly literature emphasizes the criticality of performing thorough economic impact analyses to assess the financial feasibility of biomass energy initiatives. A range of economic indicators, such as cost-benefit analyses, return on investment (ROI), and net present value (NPV), are frequently utilized to evaluate the economic aspects of these initiatives (Sun & Wang, 2021). Research makes a substantial scholarly contribution to this field by offering valuable insights into biomass energy initiatives' financial viability and prospective returns. The cohesive narrative emerges from synthesizing environmental value measurements and economic impact analyses in the extant literature, which illuminates the dual considerations essential for thoroughly comprehending the feasibility and sustainability of biomass energy projects (Sartzetakis et al., 2023). Therefore, this review provides an essential basis for subsequent research initiatives to enhance the economic and environmental dimensions of biomass energy utilization.

3 DATA AND METHODOLOGY

3.1 Theoretical Background

The study is founded upon established principles of sustainable development, economics, and environmental science. As exemplified by the Planetary Boundaries framework and the Triple Bottom Line (TBL), environmental sustainability constitutes its fundamental tenet. The importance of simultaneously addressing environmental, social, and economic aspects for sustainable development is emphasized by TBL, which is in perfect harmony with the study's emphasis on comprehensive evaluation (Huang et al., 2022). The utilization of Life Cycle Assessment (LCA) is crucial in assessing the environmental impact of biomass energy projects, underscoring the importance of conducting a thorough examination of the complete life cycle from the extraction of basic materials to their eventual disposal at the end of their useful lives. Assessing the potential economic impacts of biomass energy initiatives is grounded in neoclassical economic principles, specifically cost-benefit analysis and financial metrics such as return on investment (NPV) and ROI (Shahzad et al., 2022). The research is situated in the wider framework of global sustainability objectives, particularly the Sustainable Development Goals (SDGs) established by the United Nations. It emphasizes climate action (SDG 13) and affordable and sustainable energy (SDG 7).

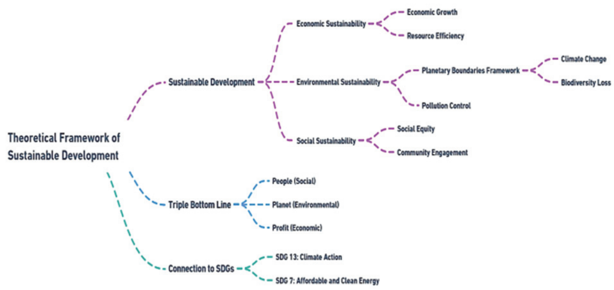

Figure 1 Theoretical framework of sustainable development

The discourse surrounding biomass energy is enriched by theoretical frameworks derived from the circular economy, including cradle-to-cradle thinking and refuse valorization. This underscores the criticality of waste reduction and resource efficiency optimization (Malliet et al., 2020). This analysis employs an interdisciplinary theoretical framework to provide a comprehensive perspective on environmental and economic aspects of biomass energy projects. This ensures a nuanced comprehension of the inherent complexities involved.

3.2 Materials and Procedures

3.2.1 Wastewater Sediment Generation

Dewatering, drying, and pelletizing were three crucial processing steps completed before the sewage sludge was burned. The raw material was first obtained from a sewage treatment plant in the Czech Republic, which had a moisture level of 95%. This moisture content was mechanically dewatered to 84 percent weight, and then it was dried in a paddle batch dryer (Chupradit et al., 2021). This stage guaranteed the creation of a standardized fuel by operating at a temperature of 180 °C on average for 60 minutes and ending with a final moisture content of 21.8 w.t.%. To preserve uniform fuel characteristics, including moisture content, the fuels kept in a regulated space inside the fuel preparation lab. Strict precautions were taken to prevent changes in the fuel properties, such as storage in airtight containers. Thorough cleaning of the combustion chamber and combustion tract before each repetition of combustion was prompted by concerns regarding the possible distortion of experimental data due to increased water vapor from the fuel's high moisture content. After drying and dewatering, the process moved on to pelletizing, which was done using an MGB 100 - BONSAI (KOVONOVÁK, Czech Republic) pelletize that had a 300 kg√h^{-1} capacity and a 6 kW power input. As a result, the

SS pellet production process produced pellets with dimensions of 25 mm in length and 5 mm in diameter.

Table 1 An in-depth examination: index of essential social skills and behavioral patterns

Factor	Symbol.	B. P	S. S	part	Ave.
Hydro.	H	4.04 ± 0.08	5.7 ± 0.01	ISO 16948	mass percent
Car.	C	29.07 ± 0.15	47.5 ± 1.06	ISO 16948	mass percent
Oxy.	O	16.53*	40.3*	ISO 16993	mass percent
Sulp.	S	0.69 ± 0.02	< 0.1 ± 0.001	ISO 16994	mass percent
Nitro.	N	2.93 ± 0.08	0.1 ± 0.01	ISO 16948	mass percent
Water	H_2O	21.8 ± 0.44	6.0 ± 0.01	ISO 18123 4-2	mass percent
Ash	Ar	24.94 ± 0.25	0.3 ± 0.01	ISO 18122	mass percent
Lower heating value	LH Vr	9.83 ± 0.34	17.7 ± 0.54	EN 18125	mass per kilogramme

Key components with corresponding symbols, behavioral patterns (BP), social skills (SS), standards, and measurements are shown in Tab. 1. which offers a comprehensive examination of the Index of Essential Social Skills and Behavioural Patterns. According to ISO 16948, hydrogen (H) has a mass percentage of 4.04 ± 0.08 and a social skill of 5.7 ± 0.01. Following the ISO 16948 standard, carbon (C) has a BP of 29.07 ± 0.15 and an SS of 47.5 ± 1.06. When measured in mass percent according to ISO 16993, oxygen (O) has a BP of 16.53* and a SS of 40.3*. Per ISO 16994, sulfur (S) has a boiling point (BP) of 0.69 ± 0.02 and a specific surface area (SS) of less than 0.1 ± 0.01. Following ISO 16948, nitrogen (N) illustrates a BP of 2.93 ± 0.08 and a SS of 0.1 ± 0.01. Following ISO 181234-2, water (H2O) has a boiling point (BP) of 21.8 ± 0.44 and a specific surface area (SS) of 6.0 ± 0.01. According to ISO 18122, ash (Ar) has a boiling point (BP) of 24.94 ± 0.25 and a specific gravity (SS) of 0.3 ± 0.01. According to EN 18125, the Lower Heating Value (LHVr) reveals a BP of 9.83 ± 0.34 and an SS of 17.7 ± 0.54, expressed in mass per kilogram. This table describes the elements' makeup and traits, shedding light on their basic social abilities and behavior patterns (Blümer et al., 2020).

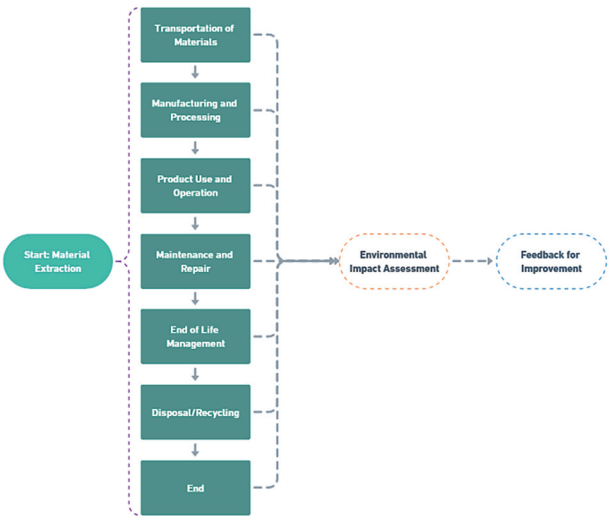

Figure 2 Life cycle assessment (LCA) flowchart for biomass energy projects

3.2.2 Production of Biomass Pellets

BP was created from a softwood mix using state-of-the-art technology to recycle biomass derivatives and wood. Using a K100 mini pellet from Comfier, Italy, two rollers powered by an electric motor were used to compress sawdust through a matrix to create pellets (Li et al., 2022). The ultimate dimensions of the pellets were 5 mm in diameter and 15 mm in length.

3.2.3 Setup for a Fluidized Bed Combustor

A fluidized bed combustor, a pilot-scale device with a maximum fuel capacity of 4.5 kg^{-1}, was used in the experiment. Fuel was provided via a screw conveyor. A 7 kW electric resistance heater was used to heat the procedure. At a maximum flow rate of 57 $m^3 \cdot h^{-1}$, the incinerator air was injected via the fluidized bed's bottom. In this configuration, a resistive heater was used to get the incinerator air temperature up to 400 °C. A 300 $m^3 \cdot h^{-1}$ smoke fan was used to make it easier for the flue gas to be released into the chimney, simplifying the vacuum required for effective functioning. By simulating real-world circumstances, this equipment design and configuration sought to provide important insights into the combustion process at the pilot scale inside the fluidized bed combustor. The main airflow ranged from 31.7 to 35.0 $m^3\sqrt{h^{-1}}$, while the fuel supply varied from 2.7 to 4.1 $kg\sqrt{h^{-1}}$ (Ayad et al., 2023). The temperature range for incineration was 915~939 °C. The average of three experimental measurements lasting one hour was used to calculate the obtained results. The measurement error was calculated as the total of the two uncertainties, A and B, or the Combined Standard Uncertainty (u_c). Standard uncertainty type A (u_A) is a form of uncertainty that results from random mistakes that have unknown origins and decreases as the number of measurements is increased. The experimenter determines and assesses the known and estimable sources of standard uncertainty type B (u_B).

$$u_c = \sqrt{{u_A}^2 + {u_B}^2} \tag{1}$$

The compound uncertainty (u_c) is determined by using Eq. (1), which takes the square root of the total squared individual uncertainties (u_A and u_B). A percentage is used to express the outcome. This formula widely calculates the total uncertainty related to combined variables in measurement and analysis.

3.3 Model-1

3.3.1 Setup Determination of Energy Recovery

The heat recovery from burning 1 kg of fuel was calculated by the above equations to evaluate the increased energy flue gases' recovery potential from the combustion of SS and BP. These measure the amount of energy removed from the combustor by the incineration gases. The flue gas volume and actual enthalpy of the gas served as the foundation for the computation of the consequent heat production (Lin & Jia, 2018). The combined enthalpy of the flue gas and the surrounding air is known as the "real flue gas enthalpy". Every value was converted to standard conditions, which are 273.15 K and 101,325 Pa.

$$\begin{aligned} h_{\mathrm{fg,min,s}} &= V_{\mathrm{CO2}} \cdot h_{\mathrm{CO2}}^{t} + V_{\mathrm{SO2}} \cdot h_{\mathrm{SO2}}^{t} + V_{\mathrm{CO}} \cdot h_{\mathrm{CO}}^{t} + \\ & V_{\mathrm{NOx}} \cdot h_{\mathrm{NOx}}^{t} + V_{\mathrm{N2}} \cdot h_{\mathrm{N2}}^{t} + V_{\mathrm{CH4}} \cdot h_{\mathrm{CH4}}^{t} + V_{\mathrm{NH3}} \cdot h_{\mathrm{NH3}}^{t} + \\ & + V_{\mathrm{HCl}} \cdot h_{\mathrm{HCl}}^{t} + V_{\mathrm{HF}} \cdot h_{\mathrm{HF}}^{t} + V_{\mathrm{H2O}} \cdot h_{\mathrm{H2O}}^{t} + \\ & + a_{\mathrm{fa}} \cdot A^{r} \cdot h_{\mathrm{fa}}^{t} \left[\mathrm{MJ} \cdot \mathrm{m}^{-3} \mathrm{N} \right] \end{aligned} \quad (2)$$

$$h_{\mathrm{air,min}} = V_{\mathrm{air,min}} \cdot h_{\mathrm{air}}^{t} + (\nu - 1) V_{\mathrm{air,min}} \cdot h_{\mathrm{H2O}}^{t} \left[\mathrm{MJ} \cdot \mathrm{m}^{-3} \mathrm{N} \right] \quad (3)$$

Concerning different components (CO_2, SO_2, CO, NO_x, N_2, CH_4, NH_3, HCl, HF, H_2O), their corresponding volumes (V), enthalpies (h), and an extra term involving an area (A) raised to a power (r), Eq. (2) computes the minimum specific enthalpy (h_{fg} (min, s)) of a gas combination. The outcome is expressed in MJ√m^{-3}N. The volume of air (V_{air} (min)), the enthalpies of air (h_{air}) and water vapor (h_{H2O}), and a term involving the specific heat ratio (ν) are all included in Eq. (3) to calculate the minimal specific enthalpy of air (h_{air} (min)). The result is given in terms of MJ√m^{-3}N. These formulas are crucial for thermodynamic investigations, especially when figuring out the energy properties of air and gas mixtures.

$$h_{\mathrm{fg},r} = h_{\mathrm{fg,min},S} + (\lambda - 1) \cdot h_{\mathrm{air,min}} \left[\mathrm{MJ} \cdot \mathrm{m}^{-3} \mathrm{N} \right] \quad (4)$$

$$Q_{\mathrm{fg}} = V_{\mathrm{fg}} \cdot h_{fg,r} \left[\mathrm{MJ} \cdot \mathrm{kg}^{-1} \mathrm{N} \right] \quad (5)$$

Eq. (4) determines the specific enthalpy ($h_{\mathrm{fg},r}$) of a gas mixture by adding the air's specific enthalpy ($h_{\mathrm{air,min}}$) to the minimum specific enthalpy of the gas mixture ($h_{\mathrm{fg,min},S}$), taking into account the heat of vaporization. It comes out to MJ√m^{-3}N. By multiplying the gas mixture's volume (V_{fg}) by the specific enthalpy determined in Eq. (4) for each unit mass, Eq. (5) computes the heat transfer (Q_{fg}). The result is given in MJ√kg^{-1}N. Fundamental to the study of thermodynamics. These equations aid in measuring enthalpy changes and energy transfer in gas mixtures (Eisen et al., 2020).

3.3.2 Life Cycle Assessment (LCA)

The environmental impacts were evaluated using the Life Cycle Assessment (LCA) analytical approach while complying with (Fakher, 2019). There are no explicit criteria for choosing an LCIA technique, according to ISO 14040/14044 (Galeotti et al., 2020), while some organizations suggest using specific LCIA methods or components. This study aims to measure and contrast the environmental effects of co-incinerating SS and BP. The following five fuel blend ratios were investigated: 100% BP, 75% BP and 25% SS, 50% BP and 50% SS, 25% BP and 25% SS, and 100% SS. Recipe 2016v 1.1 (H), utilizing midpoint characterization variables frequently used in Europe, was the selected LCIA approach for assessing environmental consequences (Cologna et al., 2022). Although the chosen LCIA technique concentrates on several impact categories, midpoints, and endpoints, the functional unit (FU) that symbolizes the fuel product system's energetic potential was determined to be 30 minutes of incineration, which corresponds to the necessary temperatures of 915-939 °C.

Although LCAs usually involve extensive cradle-to-grave investigations (Moussa et al., 2020) this study takes a gate-to-gate approach, focusing only on the incineration process of fuel blends. The limits are limited to raw material input and specific categories of pollutants output. Notably, the LCA provides a narrowly restricted viewpoint on cremation by only considering pollutant production values.

Table 2 Examining fuel variability: inventory data

Fuel B. Ratio	BP	B P 3:1 S S	B P 1:1 S S	B P 1:3 S S	S S
LHV / MJ/kg	17.7	15.7	13.8	11.8	9.83
Oil sum / kg	1.34	1.44	1.55	1.91	2.04
Ash substance / kg	0.01	0.09	0.20	0.36	0.51
Flue gases / kg	12.61	11.67	11.56	12.88	0.54
Water in / kg	0.73	0.81	0.91	1.09	1.20
Carbon dioxide / kg	0.99	0.89	1.05	0.98	1.02
Carbon monoxide / mg	633	668	176	475	576
Nitrogen oxides / mg	4468	12330	888	8890	2817
Ammonia / mg	26.7	33.0	21	30.8	26.4
Hydrochloric / mg	141.4	592.5	12.1	191.2	48.7
Sulfur dioxide	7139	18452	118	14485	3325
Methane / mg	7.6	14.2	8.5	9.9	6.4
Ethanein / mg	2.9	1.3	1.4	5.5	3.4
HF / mg	8.6	19.7	5	11.6	7
Mass of O_2 / kg	2.08	2.38	1.71	2.38	1.97
Mercury / µg	46.9	89.1	7.7	69.2	32
N_2 / kg	7.58	8.12	9.13	8.40	7.87

Tab. 2 presents a detailed analysis of fuel variability using inventory data, illustrating alternative fuel blending ratios (B. Ratio) and their corresponding parameters. When the blending ratio changes from 3:1 to 1:3, the lower heating value (LHV) in megajoules per kilogram (MJ/kg) decreases from 17.7 to 9.83. Accordingly, there are variations in the composition of water, ash substance, flue gases, and oil total in kilograms. The emissions of carbon dioxide, carbon monoxide, nitrogen oxides, ammonia, hydrochloric acid, sulfur dioxide, methane, ethane, HF (hydrofluoric acid), the mass of oxygen, and mercury are further broken down in the table in terms of kilograms and milligrams. Interestingly, there are fluctuations in the emissions with blending ratios, revealing information about how different fuel compositions affect the environment. For example, when the blending ratio changes from 3:1 to 1:3, nitrogen oxide (NO_x) emissions drop from 888 mg to 2817 mg. Similarly, the ratio shift causes the carbon dioxide emissions to rise from 8890 kg to 12330 kg. This extensive table provides a useful evaluation of the effects of fuel blending ratios on the energy content and pollutants that arise from combustion (Shahbaz et al., 2018).

3.3.3 The Analyses Conducted

Supplementary information for the assessment of fuel was acquired using both proximate and ultimate analyses (UPA) in compliance with pertinent ISO 29541:2010, ISO 19579:2006, ISO 687:2010, and ISO 1171:2010 standards.

The raw materials' bulk concentrations of Cr, Hr, Nr, Sr, Or, Wr (water), and Ar (ash) were determined. Using CHNS628 and CHNS628S analyzers (both Lecco, USA), the content of selected components was ascertained using the thermo gravimetric (Dumas) method. It can be used to study the thermal stability and composition of fuel by measuring the relationship between the mass of fuel and the temperature change under the condition of programmed temperature control. Following the EN 16993 standard, the amount of O2 was computed as a gravimetric difference after the sample was heated above the water's boiling point in a VF110 electric furnace (Memmert, Germany) in compliance with ISO 181234-2. Using a LEO 5/11 furnace (LAC, Czech Republic), the air content was measured following ISO 18122. The ISO 18125 standard was used to determine the lower calorific value or LHV.

Flue gas was subjected to Fourier transform infrared spectroscopy (FTIR) by an Atmosphere gas analyzer (Protea, UK) for qualitative and quantitative assessment. CO, CO_2, NO, NO_2, N_2O, NH_3, HCl, SO_2, CH_4, HF, and O_2 were evaluated by this analyzer. For every compound, calibration data showed an average inaccuracy on full scale with an overall uncertainty range of 0.1-5.98%. A linearity test that complied with EN 15267-3:2007, Annex C requirements was carried out. An HM-1400 TRX (Total Resistance Exercise) mercury analyzer (Drag, Germany) was used in a subsequent mercury analysis to track total mercury, which is the total elemental and oxidized mercury. It was estimated that the relative enlarged uncertainty was 5.5%.

Table 3 Meeting criteria: emission limits for stainless steel waste as specified

Pollutant	Element	Release bound
SO_2	unit of concentration (mg·m^{-3}N)	41
HCl	unit of concentration (mg·m^{-3}N)	9
HF	unit of concentration (mg·m^{-3}N)	2
CO	unit of concentration (mg·m^{-3}N)	51
NH_3	part of absorption (mg·m^{-3}N)	11
Mercury	part of measurement [µg·m^{-3}N]	21
NO_x (as NO_2)	unit of concentration (mg·m^{-3}N)	151

Tab. 3 outlines the prescribed limits for several contaminants emitted from stainless steel trash, specifying the exact conditions for meeting the requirements. The level of contaminants is quantified in [mg·m^{-3}N], except mercury, which is quantified in [µg·m^{-3}N]. The specified limitations are as follows: 41 mg·m^{-3}N for Sulphur Dioxide (SO_2), nine mg·m^{-3}N for Hydrochloric Acid (HCl), 2 mg·m^{-3}N for Hydrofluoric Acid (HF), 51 mg·m^{-3}N for Carbon Monoxide (CO), 11 mg·m^{-3}N for Ammonia (NH_3), and 151 mg·m^{-3}N for Nitrogen Oxides (NO_x, as NO_2). Furthermore, the stipulated limit for mercury discharge is set at 21 µg·m^{-3}N. These restrictions function as vital reference points, guaranteeing that emissions from stainless steel trash comply with established environmental regulations. Monitoring concentrations within these limits is crucial to comply with regulations, which helps reduce potential environmental damage and protect air quality (H. Xu et al., 2020).

3.4 An Integrated Method for Etherification and Cost Estimation in Chemical Processes

Model-2

The reactor is abbreviated as REQUIL, which was used to esterify bio-oil to create Fatty Acid Methyl Esters (FAMEs). And it is popular as biodiesel. In this procedure, a 1-weight percent potassium hydroxide (KOH) catalyst was present when the bio-oil and an excess of methanol reacted. Atmospheric pressure and 65 °C were the reaction temperatures that were maintained. This regulated atmosphere made it easier for the bio-oil to transform into FAMEs, an approved and long-lasting biodiesel. Glycerol, a by-product of the esterification process, was also successfully recovered from the biodiesel as a secondary result. This comprehensive strategy guaranteed effective by-product management besides producing biodiesel, which enhanced the overall sustainability and resource efficiency of the esterification process.

$$\begin{aligned}&\text{Oleic acid}\left(C_{18}H_{34}O_2\right)+\text{Methanol}\left(CH_3OH\right)\leftrightarrow\\&\text{Methyl-Oleate}\left(C_{19}H_{36}O_2\right)+\text{water}\left(H_2O\right)\end{aligned}\tag{6}$$

$$\begin{aligned}&\text{Palmiticacid}\left(C_{16}H_{32}O_2\right)+\text{Methanol}\left(CH_3OH\right)\leftrightarrow\\&\text{Methyl-Palmitate}\left(C_{17}H_{34}O_2\right)+\text{water}\left(H_2O\right)\end{aligned}\tag{7}$$

$$\begin{aligned}&\text{Linoleicacid}\left(C_{18}H_{32}O_2\right)+\text{Methanol}\left(CH_3OH\right)\leftrightarrow\\&\text{Methyl-Linoleate}\left(C_{19}H_{34}O_2\right)+\text{water}\left(H_2O\right)\end{aligned}\tag{8}$$

$$\begin{aligned}&\text{Aceticacid}\left(C_2H_4O_2\right)+\text{Methanol}\left(CH_3OH\right)\leftrightarrow\\&\text{Methyl-Acetate}\left(C_3H_6O_2\right)+\text{water}\left(H_2O\right)\end{aligned}\tag{9}$$

$$\begin{aligned}&\text{Formicacid}\left(CH_2O_2\right)+\text{Methanol}\left(CH_3OH\right)\leftrightarrow\\&\text{Methyl-Formate}\left(C_2H_4O_2\right)+\text{water}\left(H_2O\right)\end{aligned}\tag{10}$$

In the process of producing biodiesel, transesterification reactions are represented by Eqs. (6), (7), (8), (9), and (10). Fatty acids (Oleic, Palmitic, Linoleic, Acetic, and Formic acid, respectively) react with methanol in these reactions to form the corresponding methyl esters (Oleate, Palmitate, Linoleate, Acetate, and Formate) as well as water. Triglycerides in fats and oils are converted into biodiesel through a critical process called transesterification, which helps provide renewable and sustainable fuels (Rehman et al., 2023).

$$C_1=C_0\cdot\left(\frac{S_1}{S_0}\right)^{0.6}\tag{11}$$

A relationship between concentrations is expressed by Eq. (11), in which the initial concentration is denoted by C_0 the final concentration by C_1; moreover, the associated solubilities by S_0 and S_1. Based on solubility ratios, the equation models the concentration change using a power factor of 0.6. In the chemical and environmental sciences, this kind of equation is frequently used to represent the equilibrium concentration in a solution (Du & Wang, 2023).

$$\begin{aligned}&\text{New equipment cost}=\\&\text{Base equipment cost}\times\frac{\text{2022cost index value}}{\text{Base year cost index value}}\end{aligned}\tag{12}$$

Eq. (12) determines the cost of new equipment by comparing the current year (2023) to a base year and using the cost index value. The base equipment cost is multiplied by the ratio of the cost index value for 2023 to the cost index value for the base year in the formula. In order to account for inflation or shifts in the price of labor and commodities over time, this equation is frequently employed in cost estimating.

Table 4 The parameters related to operating costs

Substance	E. cell
Helium / \$/ton	12
Biomass cost / \$/ton	80
Turn on the vehicle / \$/tonne	2100
KOH is equivalent to / \$/tonne	2600
Methanol / \$/tonne	700
Utilities	
\$/kW-hr for electricity	0.08
Water for cooling / \$/m^3	0.07

Tab. 4 summarizes important operational cost characteristics, including the financial implications of different materials and utilities. Helium is defined to cost \$12 per tonne, but the cost of biomass is \$80 per tonne. The cost to initiate the vehicle is \$2100 per tonne, whereas the same cost for KOH is \$2600 per tonne. The cost of methanol is \$700 per tonne. Utility expenditures include water for cooling at \$0.07 per m^3 and electricity at \$0.08 per kW-hr. These variables are essential for comprehending the operational processes' financial environment, which helps evaluate the overall cost-effectiveness and budgetary requirements. Tab. 4 decomposes the costs of drugs and utilities, which is an important resource for financial planning and operational decision-making.

Table 5 The inputs required for conducting a discounted cash flow analysis

Financial input	E. cell
Required rate of return	10%
Income Tax	40%
Revenue escalation	5%
An increase in capital costs	5%
An increase in operating costs	3%
Plant existence	20 years

The basic components required to do a discounted cash flow (DCF) analysis, a key technique in financial valuation, are listed in Tab. 5. 10% is the needed rate of return, which is a crucial criterion for determining the venture's profitability. The percentage of taxable income allotted to taxes is 40%, as stated in the income tax rate. Revenue escalation is projected to expand by 5% annually, while operating and capital costs will rise by 3% and 5%, respectively (Awosusi et al., 2022). When predicting future financial success, these escalation rates are extremely important. The investment's expected operational lifespan, or "plant life", is 20 years. These financial inputs work together to form the basis of an extensive DCF analysis, which allows for a detailed assessment of the investment's long-term financial viability and possible returns.

Tab. 6 shows how to estimate the total project investment using several parameters reported as percentages of the equipment's provided cost (TPEC). Building expenses account for 46%, repair services account for 56%, electrical system accounts for 31%, controls and instruments account for 26%, pipelines account for 10%, purchase and installation tools account for 39%, and backyard improvements account for 12%. Total installed equipment cost (T.IE.C) is calculated by multiplying TPEC by 4.20. Official and contractor fees are set at 23%, business expenditures are at 32%, structural costs are at 34%, and an emergency reserve is established at 15% of the Fixed Capital Investment (FCI). TIC is calculated by multiplying T.IE.C by a factor of 1.26, while FCI is the sum of TIEC and T.I.C. Working capital (WC) accounts for 75% of total capital investment (TCI), including FCI and WC. This systematic breakdown gives a complete way to calculate the many components that contribute to the overall project expenditure needed (F. Wang et al., 2021).

Table 6 Total project investment estimation method

Factor	Percentage of the equipment's supplied cost / %
(T.P.E.C)	1 hundred (100)
Building	46
Repair services	56
Elec. System	31
Controls and instruments	26
Pipe	10
Purchase and install tools	39
Backyard improvements	12
(T.IE.C)	T.P.E.C * 4.20
Official and contractor fees	23
Business	32
Structure	34
Emergency	15% of Fixed capital investment (FCI)
T.I.C	1.26 * TPEC
FCI	TIEC + TIC
Working capital (WC)	75
TCI	FCI + WC

3.4.1 Assessment of the environmental impact

A lifecycle assessment (LCA) methodology was used to evaluate the potential environmental effects of biodiesel production. This methodology thoroughly assesses the environmental features and implications related to the entire lifecycle of biofuel production technology using microalgae oil upgrading (MAP). Economic analyses and Aspen Plus process simulation models provided the data for this investigation. The entire biodiesel production lifespan was considered for the cradle-to-grave environmental impact assessment, using one tone of biodiesel produced as the functional unit (L. Xu, Shah, et al., 2019). The midway impact assessment technique was used in this study's Life Cycle Assessment (LCA), which used the Convent database and open LCA 2.0 software to evaluate possible global warming implications (Falcone & Sica, 2018). The evaluation focused on pine and timber production, using data from a sawmilling and forestry company in Zimbabwe's Eastern Highlands. Detailed information on input and output was gathered to examine the environmental consequences of the early phases of biofuel manufacture.

A thorough lifecycle analysis of the input and output streams in the manufacturing process is provided in Tab. 7 which covers manufacturing one ton of biodiesel. Alkyl ate-naphtha-paraffin (ANP) in various amounts, charcoal, diesel, electricity, helium, methanol, potassium chloride, sodium hydroxide, and wood sawdust are among the inputs. The products include a wide range of materials, including glycerol, acetic acid, furfural, furfural, carbon dioxide, biodiesel, charcoal, copper, dimethoate, hydrogen, iron, magnesium, manganese, methane, nitrogen dioxide, nitrogen monoxide, particulates, potassium, PI acid, and propyl benzene. This comprehensive analysis provides a comprehensive overview of the environmental effects related to biodiesel Production, illuminating the resource consumption and emissions generated across the product's lifetime. This information is essential for making well-informed choices about biodiesel production's environmental impact and sustainability (Oryani et al., 2021).

Table 7 Lifecycle assessment for manufacturing one tone of biodiesel

Stream	Element	Quantity
A.N.P	kilogram	2250
A.N.P	kilogram	50
Charcoal	kilogram	63.2
Diesel	kilogram	320
Electricity	kWh	575
Helium	kilogram	12
Methanol	kilogram	3000
Potassium chloride	kilogram	190
Sodium hydroxide	kilogram	10
Wood sawdust	kilogram	3160
Outputs		
Acetic acid	kilogram	0.92
Biodiesel	kilogram	1000
Carbon dioxide	kilogram	1170
Carbon monoxide	kilogram	100
Charcoal	kilogram	860
Copper	kilogram	16
Dimethoate	kilogram	4.4
Dinitrogen monoxide	kilogram	0.012
Ethane	kilogram	0.42
Formic acid	kilogram	1.69
Furfural	kilogram	0.62
Glycerol	kilogram	300
Hydrogen	kilogram	2
Iron	kilogram	125000
Magnesium	kilogram	26630
Mang.	kilogram	891
Meth.	kilogram	16.57
N. dioxide	kilogram	0.27
N. monoxide	kilogram	3.5
Particulates, < 10 um	kilogram	1.12
Potass.	kilogram	31100
P.I acid	kilogram	5.7
Propyl benzene	kilogram	0.16

4 RESULTS AND DISCUSSION

4.1 Assessment of Pollutants, Energy Recovery, and Life Cycle of Co-Incineration

The studies were conducted in a fluidized bed combustor, where pure SS and BP were incinerated individually and in blended ratios of 3:1, 1:1, and 1:3. The flue gas composition was evaluated under normal circumstances. The amount of air was modified to get the most efficient combustion. The levels of contaminants escalated in proportion to the increase in suspended solids content. The incineration of SS (solid waste) surpassed the prescribed limits for emissions, emphasizing the necessity for implementing pollution control measures (Diaconașu et al., 2022). The rise in moisture and acid gas concentrations in the flue gas and higher SS content have generated concerns regarding low-temperature corrosion and water conservation. The energy recovery parameter was determined based on the enthalpy and volume of the flue gas. BP demonstrated the greatest energy recuperation, decreasing linearly as the SS concentration increased. BP exhibited self-sustained combustion in its pure form, but SS in its pure form necessitated heating in a fluidized bed. The co-incineration suggestions attempted to optimize energy recovery by suggesting a practical utilization of SS (Foong et al., 2020).

Other studies have also found that mixing with SS increases reactivity and energy content. Coincineration's advantages include decreased boiler heat generation and reduced coal consumption. Co-incineration is expected to treat sewage sludge and municipal solid waste through energy recovery. Co-immolation can increase the mercury content in incineration ash and reduce the amount of mercury released into the atmosphere. The optimal mixture ratio for Hg enrichment is 54 w.t.% SS and 46 w.t.% MSW. The presence of a less dangerous chemical form of mercury reduces the risk of direct toxicity of mercury from incineration ash. The results show that co-immolation produces more gaseous mercury-0 that is oxidized to Hg2 + during cooling, thus reducing the environmental risk to the atmosphere. The Life Cycle Assessment (LCA) was conducted to evaluate the environmental consequences of the fuel mixture, considering its functional unit (FU) and the amount of energy produced during a 30-minute incineration process (L. Xu, Wang, et al., 2019). The quantity of fuel fluctuated depending on its low heating value, with pure BP having the highest LHV. The Life Cycle Assessment (LCA) utilized the ISO 14040/14044 methodology and applied the Recipe 2016 v1.1 Midpoint (H) Life Cycle Effect Assessment (LCIA) method. This approach allowed for the quantification of emissions across nine different effect categories. The findings in Fig. 5 illustrate the patterns of environmental impact within the selected categories.

4.2 Analysis of Modeling, Economics, Sensitivity, Uncertainty, and Environmental Impact

Using 2000 dry metric tons per day (MTPD) of pine sawdust, the pyro-lyses portion of the model produced 25.3 w.t.% NCGs, 8.9 w.t.% bio-char, and 65.8 w.t.% bio-oil. This is consistent with findings from earlier studies, where 48 percent of the raw bio-oil was produced as biodiesel through the etherification process. Applications for adaptable biofuel include transportation, the manufacturing of chemicals, energy, and possibly even sustainable aviation fuel (Radhakrishnan et al., 2023). Glycerol, a useful by-product used in many sectors, was also produced by the technique, providing an extra source of income. The cumulative costs of TPEC, TIEC, TIC, WC, and project contingency are included in the Total Capital Investment (TCI) for biodiesel production. These costs add up to \$41.6 MM, \$133.1 MM, \$52.4 MM, \$31.2 MM, and \$27.8 MM (Zepf, 2020). At 37.9%, the pyro-lyses section is the greatest part of the TPEC. It is followed by the bio-oil etherification section at 20.3%, biomass pretreatment at 21.4%, and pyro-lyses product recovery at 17.1%. Facilities that store biodiesel made up 3.3% of the TPEC.

Input costs, annual operating costs, and biodiesel output are highlighted concerning the minimum fuel selling price (MFSP). As the Monte Carlo analysis shows, the average MFSP of $2.49/L with low volatility indicates robust and well-managed production processes. Compared with alternative biodiesel production processes, the produced biodiesel has a lower Global Warming Potential (GWP) of 70.97 kg CO_2 eq/ton, which represents potential mitigation of climate change. Comparing the studied process with experiments that different feedstocks reveal much-reduced emissions. The observed differences in GWP values between studies result from various factors, including the choice of feedstock, production technology, and system boundaries. Biomass feedstock results in carbon sequestration and offsets emissions during production, and it may cause this study's lower GWP.

Table 8 Process yields of pine sawdust pyro-lyses enhanced by microwave

Key in	Key out	Defer (MTPD)
Biomass (2000 MTPD)	Bio-char (8.9 w.t.%)	178
	Bio-oil (65.8 w.t.%)	1316
	48.0% biodiesel made of bio-oil	631.7
Bio-oil (1316.0 MTPD)	By-products (bio-oil, 52.0% by weight)	684.3
	NC. Gs (25.3 w.t.%)	506

The process yields of the microwave-assisted paralysis of pine sawdust are shown in Tab. 8. This includes the deferred mass throughput (MTPD) values and important input and output streams. The first biomass input, 2000 MTPD (Metric Tons per Day), is pyro-lyses to create biochar and bio-oil. With 8.9 weight percent of the starting biomass, the bio-char produces 178 MTPD concurrently. Thebio-oil yields 1316 MTPD, accounting for 65.8% of the biomass (Cai et al., 2021). A portion of the bio-oil stream 48.0 weight percent of the bio-oil or 631.7 MTPD is further processed into biodiesel. 52.0 weight percent of the remaining bio-oil by-product yields 684.3 MTPD. Finally, non-condensable gases (NCGs) comprise 25.3 weight percent of the by-products and contribute 506 MTPD. Concerning biomass's mass distribution and conversion

Table 9 An overview of the economic analysis of producing biodiesel using bio-oil made from pine sawdust MAP

Cost evaluation parameter	Value
The whole cost of tools bought	$42.7 MM
Whole install tools costs	$134.2 MM
Whole yearly working costs	$165.8 MM
Least Fuel selling price	$2.31/liter
Total capital investment	$286.1 MM

A brief synopsis of the economic analysis for the generation of biodiesel from bio-oil produced by Microwave-Assisted Pyro-lyses (MAP) of pine sawdust is provided in Tab. 9. The $42.7 million total cost of purchased equipment includes purchasing necessary equipment. The total cost of installed equipment, including purchase and installation, comes to $134.2 million. It is estimated that the cost of operations will be $165.8 million per year, which represents continuing costs. The amount needed to pay for all expenses is the Minimum Fuel Selling Price, which is set at $2.31 per liter. Combining equipment and operational expenditures, the $286.1 million Total Capital Investment represents the total financial commitment. This thorough economic review helps with investment considerations and strategic decision-making by offering vital insights into the biodiesel manufacturing process's potential profitability and financial viability.

4.3 ROBUSTNESS ANALYSIS

The complex nature of these assessments must be considered when assessing the reliability of environmental value measurement and the economic effect analysis of biomass energy projects. In this application, robustness refers to the dependability and robustness of the techniques used in environmental valuation and economic impact analysis (Zheng, 2023). Robust metrics should be used in measuring environmental values, considering things like carbon sequestration, improving air and water quality, and protecting biodiversity. Thorough life cycle assessments can increase the environmental evaluation's credibility by guaranteeing that all potential effects are considered (Gouws et al., 2021). Simultaneously, the prospective economic impact ought to exhibit resilience by incorporating direct and indirect consequences on regional economies, employment generation, and market expansion. All-encompassing economic models, like input-output analysis, can better comprehend the project's financial impact. Sensitivity testing against many economic scenarios is another way to ensure the robustness of estimates under varied situations in an economic impact analysis. The amalgamation of these resilient approaches guarantees a comprehensive comprehension of biomass energy initiatives (Alem & Demeke, 2020). In addition to bolstering the project's credibility, a comprehensive economic impact study and robust environmental assessment help stakeholders, politicians make well-informed decisions. Because biomass energy is still a key component of sustainable energy portfolios, thorough analyses are necessary to maximize environmental advantages and promote long-term economic viability.

5 CONCLUSION AND POLICY RECOMMENDATION

In order to realize the sustainable development of the biomass energy industry, we should make full use of the existing biomass resources in China to break through the bottleneck of the supply of biomass resources and improve the added value of biomass energy products. To realize the production of high value-added products and understand the microstructure and change rules of different biomass, this paper adopts different production methods for different biomass resources to give full play to their biomass energy potential, so that biomass resources can be efficiently converted into biomass energy products. In conclusion, evaluating the prospective economic impact and environmental value of biomass energy projects offers important information on the viability and sustainability of these initiatives. The solid approaches in these evaluations greatly aid in making well-informed decisions as we negotiate the tricky junction of environmental preservation and economic development. Measuring environmental values is an important factor that needs careful thought. Sturdy metrics covering various topics, such as biodiversity conservation and carbon sequestration, guarantee a thorough grasp of the environmental impact. Thorough life cycle assessments play a crucial role in evaluating and assessing the overall effects of biomass energy projects, which facilitates the development of ecologically responsible regulations. Concurrently, the possible economic effect is essential to determining if biomass energy projects are generally viable. Sturdy economic models, like input-output analysis, allow for a detailed assessment of the direct and indirect effects on market expansion, job creation, and local economies. Sensitivity testing against various economic scenarios improves the robustness of economic effect forecasts and gives stakeholders and policymakers a better understanding of possible outcomes.

1. The knowledge gained from these thorough evaluations should influence future policies on biomass energy projects. Policy policymakers must prioritize integrating environmentally sustainable practices in conjunction with economic growth. Future policy should prioritize encouraging and supporting the adoption of innovative technologies that maximize economic and environmental benefits. This could involve funding R&D projects that improve biomass energy projects' overall effectiveness and environmental performance and promote the creation of novel technology for biomass conversion. However, given the current state of environmental value assessment and economic impact analysis in biomass energy projects, it is imperative to recognize some limitations.

2. The quality and accessibility of data, especially in poorer nations, might make judgments less accurate. Coordinated efforts needed to overcome these constraints, which enhance the infrastructure for data gathering, and encourage reporting openness. Furthermore, inherent uncertainties are introduced by the dynamic nature of environmental science and economic modeling. Therefore, policymakers must acknowledge the dynamic character of the assessments. Given these constraints, there is a chance for more multidisciplinary cooperation between economics, politicians, and environmental scientists. Through this partnership, more advanced approaches can be developed and refined, this can address present shortcomings, and improve the precision and application of environmental and economic impact assessments.

3. In conclusion, establishing a sustainable balance between environmental preservation and economic development depends on integrating rigorous environmental value evaluation and economic effect analysis in biomass energy projects. Insights from these evaluations should be incorporated into future policy to foster an atmosphere supporting the expansion of biomass energy projects. Identifying and resolving present constraints improved data infrastructure and interdisciplinary cooperation, which will guarantee these evaluations' sustained applicability and efficacy in steering the course toward a more economically feasible and sustainable energy future.

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