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Techno-Economic Stepwise Analysis Approach for Optimization of Bioethanol Production from Zambian Corn Stover: Environmental and Economic Implications

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Abstract

The paper examined the techno-economic feasibility of bioethanol production from corn stover in Zambia using a stepwise analysis approach. The research integrated technical efficiency with economic viability to optimize bioethanol production while addressing environmental concerns. The analysis covered capital investment, operational costs, revenue projections, and environmental benefits associated with ethanol adoption. Findings indicated that a 50,000-liter-per-day bioethanol plant required an initial capital investment of $5.62 million, with an estimated production cost of $0.21 per liter. The payback period was projected at 2.78 years, demonstrating financial viability. Furthermore, the introduction of E10 blending in Zambia was expected to reduce greenhouse gas emissions by approximately 10%, improve air quality, and lower fuel costs. The projected pump price for blended fuel (E10) was estimated at $1.0762 per liter compared to the current gasoline price of $1.1724 per liter, reflecting an 8.2% reduction in fuel costs. Beyond economic gains, bioethanol adoption would significantly reduce carbon monoxide and particulate matter emissions, contributing to a cleaner environment and improved public health. Additionally, the shift to E10 was estimated to cut carbon dioxide equivalent (CO_2e) emissions by approximately 136,628.69 metric tons annually, supporting Zambia's climate mitigation goals. The study highlighted bioethanol's potential to enhance energy security, minimize petroleum dependency, and create economic opportunities for farmers and industries involved in bioethanol production.

Keywords

Bioethanol, Techno-Economic Analysis, Maize Stover, E10 Fuel Blending, Greenhouse Gas Emissions, Energy Security

1. Introduction

Techno-economic analysis (TEA) is a critical approach for evaluating the feasibility of bioethanol production by integrating technical efficiency with economic viability. It plays an important role in transitioning bioethanol production from laboratory-scale experiments to industrial-scale applications [1]. Laboratory-scale studies provide essential data on process efficiency, yield optimization, and reaction kinetics, but TEA ensures that these findings are translated into economically feasible industrial processes. Also, bioethanol production from lignocellulosic biomass, particularly agricultural residues such as corn stover, is gaining prominence due to its potential to enhance energy security, mitigate environmental pollution, and reduce dependency on fossil fuels [2]. The most compelling motivations for bioethanol adoption are its nature to minimize greenhouse gas (GHG) emissions. Studies indicate that bioethanol combustion emits substantially lower levels of carbon monoxide (CO), sulfur dioxide (SO_2), and particulate matter (PM) compared to conventional gasoline, contributing to improved air quality and climate change mitigation [3]. Implementing an E10 fuel blend (10% bioethanol, 90% gasoline) could lead to significant emissions reductions in Zambia's transport sector, aligning with global carbon neutrality goals. Moreover, utilizing corn stover for bioethanol production assists in preventing the common practice of open-field burning, which is a significant source of air pollution and CO_2 emissions [4].

2. Related Work

Previous studies have utilized different TEA methodologies, which include process simulation-based assessments, life cycle costing, Monte Carlo simulations, and cost-benefit analyses, each offering unique insights into cost estimation and risk analysis. Process simulation enables researchers to model and optimize the production process virtually, while life cycle costing provides a long-term perspective on economic sustainability [5]. Monte Carlo simulations, on the other hand, help in evaluating uncertainties and risks associated with cost fluctuations, making them particularly useful for investment decisions [6]. The stepwise TEA methodology is an emerging structured and adaptable tool for systematically evaluating bioethanol production through well-defined stages. It integrates both technical feasibility and economic viability, making it particularly valuable for optimizing production pathways, especially in developing regions like Zambia [7].

This study applied the stepwise TEA approach to assess the economic potential of bio-ethanol production from Zambian corn stover, with insights into process optimization, emissions reduction, and cost-effectiveness [8]. Zambia's agricultural sector generates substantial amounts of corn stover, an underutilized lignocellulosic biomass with high potential for bioethanol production. The Food and Agriculture Organization (FAO) research in 2020 reported that Zambia produced 2,777,713 tons of maize stover and 552,595 tons of maize cobs. These large biomass quantities are typically burned as waste, contributing to air pollution and lost economic potential [9]. By diverting these residues toward bioethanol production, Zambia can achieve multiple benefits, including environmental sustainability, waste valorization, and enhanced energy security.

Based on average maize yields of 2.5 to 3.5 tons/ha and sustainable stover removal rates of 30% - 40%, Zambia's potential annual supply of corn stover (maize residue) is estimated to be between 2 and 4 tons per hectare (FAO, 2020). An estimated 150,000 to 300,000 dry tons of maize stover could be produced annually in areas with high maize production, such as the Eastern, Central, and Southern Provinces, within a sourcing radius of 50 to 70 kilometers (ZARI, 2021). The establishment of safe feedstock storage systems, such as baling and covered storage, is required to guarantee year-round availability, because Zambian maize harvesting is seasonal, with the main harvest between April and July (IRENA, 2018).

The purpose of this study is to evaluate the feasibility and economic viability of converting maize stover into bioethanol using a stepwise TEA methodology. This approach assesses key factors such as feedstock availability, conversion processes, production costs, and market conditions [10]. It also examines the environmental impact of bioethanol adoption, focusing on emission reductions and energy security improvements [11].

The aims of this research were to identify the most cost-effective production pathways by optimizing pretreatment, enzymatic hydrolysis, and fermentation processes. A detailed techno-economic evaluation was to determine the financial viability of large-scale bioethanol production in Zambia [12]. The study also sought to analyze potential policy and infrastructure requirements to support a sustainable bioethanol industry [13].

The findings of this study can be valuable to multiple stakeholders. Farmers can benefit from selling corn stover as an additional revenue source. The biofuel industry can use the insights to establish cost-effective production facilities [14]. Government policymakers can develop strategic policies to encourage bioethanol production and blending mandates. Additionally, consumers may benefit from stabilized and reduced fuel prices due to the integration of cost factors with the higher gasoline cost and the lower bioethanol cost [15].

Despite the global momentum in lignocellulosic bioethanol research, fewer studies are being conducted on techno-economic feasibility in the African context, especially in Zambia. Most research normally focuses on regions such as the United States and China, where the biofuel industry is already well established. These regions have different economic, climatic, and infrastructural conditions, making their findings less applicable to Zambia [16]. Additionally, existing TEA studies rarely integrate the full scope of environmental and economic benefits, such as the impact on gasoline pump prices and national energy policies [17].

This study's novelty lay in its focus on optimizing bioethanol production from Zambian corn stover through a detailed techno-economic analysis. By tailoring the production process to local feedstock properties and Zambia's economic landscape, the research addressed unique challenges and opportunities within the region [18]. Moreover, while past studies have largely focused on conventional prtreatment and conversion techniques, this research aimed to integrate advanced processing technologies, such as deep eutectic solvents, which have not been explored in Zambia. This innovative approach made a significant contribution to the field of bioethanol production from lignocellulosic biomass [19].

3. Methodology

This analysis utilized the stepwise techno-economic analysis (TEA) approach to evaluate the feasibility of bioethanol production from corn stover in Zambia. The methodology integrated both technical and economic assessments, covering capital expenditure (CapEx), operational expenditure (OpEx), and key economic performance indicators [20]. A conceptual framework was utilized to estimate costs, optimize production efficiency, and analyze financial viability through net present value (NPV) and payback period calculations. Also, sensitivity analyses were used to assess potential risks associated with market fluctuations. This approach ensured a comprehensive evaluation of the economic and environmental sustainability of scaling bioethanol production to an industrial level [21].

3.1. Capital Cost Estimation

Capital costs included one-time investments required for facility construction, equipment acquisition, and site preparation. These encompassed expenses such as fermentation tanks, distillation columns, molecular sieves, ethanol storage tanks, piping systems, and steam boilers [22]. The required fermentation tank capacity was estimated using:

$$V_c = \frac{Q \cdot D}{t_w} \tag{1}$$

Where:

Q is the total bioethanol production volume per year (L/year).

D is the number of operational days per year (300 days/year).

t_w is the plant's working hours per day (24 hours/day).

V_c is the fermentation tank capacity or volume

The calculated V_c value was used to estimate the construction costs (CC) using Equation (2)

$$CC = V_c \cdot C_p \tag{2}$$

where:

C_p is the unit cost of constructing a fermentation tank (obtained from supplier quotes).

Figure 1 shows the flowchart outlining the stepwise methodology used in the study

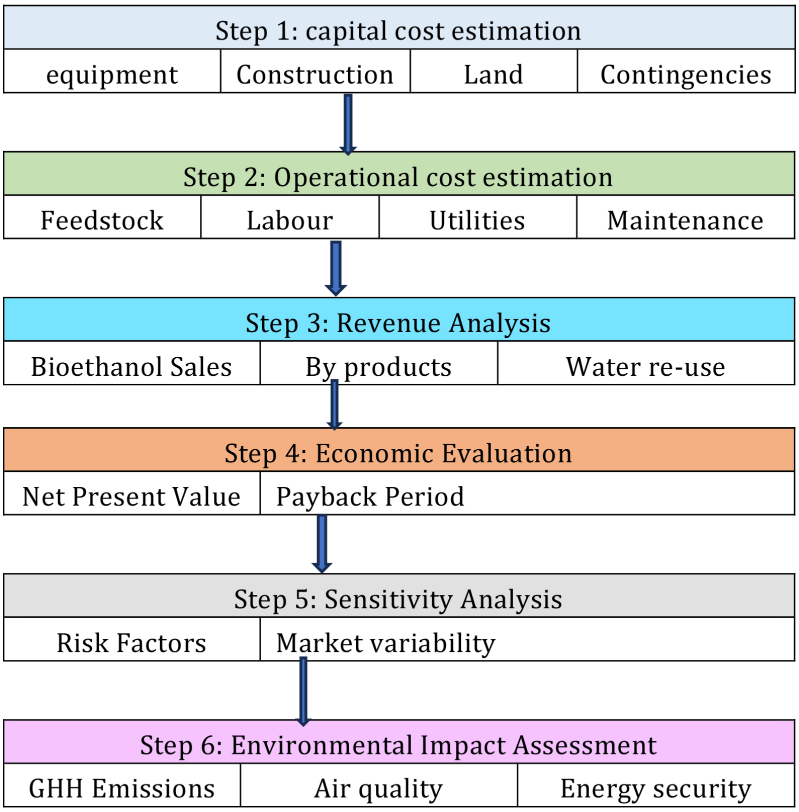

Figure 1. Flowchart outlining the stepwise methodology used in the study.

The machinery and equipment costs include fermentation tanks, distillation columns, molecular sieves, ethanol storage tanks, pumps, and steam boilers. These costs were calculated based on the plant's required production capacity and quotes from suppliers.

Additional costs, such as electrical wiring, piping, and site works, were factored in using coefficients derived from previous studies. Land acquisition was estimated at 1.5% of the total capital investment costs. Contingencies, contractor charges, and engineering consultancy fees were estimated as percentages of the total construction cost [23].

3.2. Operational Costs

Operational costs included feedstock procurement, energy consumption, labor, water, maintenance, and taxation. The plant required 200 tons of corn stover per day, with energy consumption evaluated based on the power demands of distillation, fermentation, and cooling systems [24]. Process water requirements were determined by considering usage in feedstock preparation, fermentation, and cooling processes. Maintenance and repair costs were estimated at 1.5% of the total capital costs, while government taxes and worker salaries were estimated at 1% and 2%, respectively [25].

Optimization strategies were integrated to reduce operational costs, including bulk purchasing agreements for feedstock and energy-efficient technologies to lower electricity consumption [26]. Efforts to optimize operational costs included reducing feedstock costs by negotiating bulk purchase discounts and implementing energy-efficient technologies to lower electricity costs.

3.3. Revenues, Net Present Value, and Payback Period

The revenue projections considered income from bioethanol sales and by-products, such as carbon dioxide for industrial applications and residual biomass for animal feed. The economic benefits of the plant include revenue from the reuse of treated process water. Sensitivity analyses were performed to evaluate financial risks under market fluctuations, with adjustments for inflation and taxation [27].

Several tools for economic evaluation were used to present a comprehensive view of the investment costs and benefits of the project. The fundamental tools included Net Present Value (NPV) and Payback Period (PB), which help determine the financial viability of bioethanol production. The NPV reflects the project's profitability by discounting future cash flows, while the PB assesses the duration required to recover the initial investment [28]. A shorter PB indicates a more attractive investment., such as carbon dioxide for industrial applications and residual biomass for animal feed. Sensitivity analyses were performed to evaluate financial risks under market fluctuations, with adjustments for inflation and taxation [29].

This structured TEA methodology provides a comprehensive evaluation of technical and financial feasibility, supporting investment decisions and policy formulation for sustainable bioethanol production. The NPV of a project reflects the worth of the project. The payback period is the time it takes to recover the cost of an investment [30]. It is determined by dividing the initial investment by the average cash flows. A payback period that is shorter, makes an investment more attractive than one that is longer. An average inflation rate in Zambia of 11.04% (average from 2005 to 2024) is used [31].

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^i} - \text{Initial Investmen} \quad (3)$$

Where:

- CF_t is the cash flow at time *t*.
- r is the average discount or inflation rate (11.04% or 0.1104) for the period 2005 to 2024.
- n is the project lifespan
- Initial Investment is the total capital cost.

Changing the discount rate used to value future cash flows changes the Net Present Value (NPV) when you use a standard cost of capital. The NPV goes up if the standard rate is lower than the original, which makes the project look better. The

NPV goes down if the standard rate is higher, which could make the project less viable. Using a standard rate makes sure that evaluations are consistent, but it might not accurately reflect the risk of a specific project, which could lead to bad investment choices.

The payback period is useful when making investment decisions even though it does not consider the time value of money [32]. The annual profits were calculated by subtracting operational costs from total revenues, and the payback period was determined using Equation (4):

$$\text{Payback Period} = \frac{Total\ capital\ cost\,(\$)}{annual\ profit\,(\$/year)} \tag{4}$$

The analysis showed that the use of optimized processes, including efficient distillation and dehydration technologies, improved profitability.

Based on market projections for renewable fuel alternatives and regional fuel pricing benchmarks, the ethanol selling price of $1.50 per litre was assumed. This price is consistent with recent developments in the biofuel market in southern Africa, where imported ethanol products range in price from $1.40 to $1.60/L, contingent on blending policy incentives, purity, and grade ([33]). This price was also tested across a range of $1.20 to $1.70 per litre to assess the impact on profitability and the payback period, taking into account market volatility and policy changes.

4. Results and Discussion

The results of this study present a detailed techno-economic analysis of bioethanol production from corn stover, assessing both laboratory-scale and industrial-scale feasibility. Key findings include cost estimations, revenue projections, environmental benefits, and the impact of E10 fuel blending on Zambia's energy sector. The discussion interprets these findings in the context of economic viability, investment attractiveness, and environmental sustainability, providing insights into the potential for large-scale bioethanol adoption.

4.1. Laboratory-Scale Expenditure Analysis

Table 1 provides a breakdown of the expenditure for lab-scale bioethanol production, detailing the costs associated with essential inputs such as enzymes, yeast, fermentation tests, and support staff wages.

Table 1. Laboratory-scale material quantities and costs.

Item	Price in Zambian Kwacha (K)	Price in US Dollars ($)
Lactic acid/choline chloride	40,500	1,500
Corn *stover* purchase/grind/transport	5,000	186
Cellulase enzymes	15,000	556
Saccharomyces cerevisiae yeast	270	10
Fermentable sugar tests	8,000	300

Continued

Alcohol level tests	20,000	800
Purchase of utensils	10,000	400
Support staff wages	20000	800
Total	**118,270**	**4,552**

This table offers a bill of quantities for various components that are also present in the industrial-scale TEA. The expenditure analysis at this stage helps understand the key cost drivers before scaling up production.

4.2. Techno-Economic Analysis (TEA) of Industrial-Scale Production

Table 2 presents the TEA for industrial-scale bioethanol production, outlining the capital and operating costs required for a plant with a daily production capacity of 50,000 liters. The capital cost section includes significant expenditures such as fermentation tanks, distillation columns, storage tanks, and process infrastructure. Notably, some items in Table 2 derive their unit costs and justifications from the expenditure analysis in Table 1, allowing for a more structured cost assessment.

Table 2. Techno-economic analysis of bioethanol production.

	Description	Justification	Bioethanol		
			%	Unit	cost
Capital costs	Land acquisition	≈ 1.5% of all other capital costs	1.50	$	84,367.50
	Fermentation tanks	Based on the plant capacity (~50,000 liters/day), 4 tanks are required.	11.36	$	637,489.20
	Pumps for transferring liquids	Includes pumps for feedstock, mash, and ethanol transfer.	4.87	$	273,695.63
	Ethanol storage tanks	Construction of intermediate and final ethanol storage tanks.	3.25	$	182,805.15
	Pre-treatment tanks	Includes the preparation of feedstock (enzymatic hydrolysis).	3.21	$	179,963.28
	Pipes and valves	Connects tanks, fermenters, and distillation columns.	0.97	$	54,361.13
	Distillation columns	Two continuous columns for ethanol separation.	22.49	$	1,260,345.98
	Molecular sieves for dehydration	Produces fuel-grade ethanol (>99.5% purity).	6.49	$	364,481.03
	Stirrer motor	Ensures mixing during fermentation. Magnetic stirrers, ovens (various).	3.90	$	218,812.39
	Washing and filtration tank	For removing residues from the fermentation broth.	1.94	$	108,732.81
	Steam boiler	Provides heat for distillation processes.	1.72	$	96,738.69
	Construction works, including the installation of tanks, piping, valves, electrical works, and site works	Includes installation of tanks, piping, electrical work, and site preparation.	12.99	$	727,482.34

Continued

	Contractor charges	0.15(CC + CC/0.4)	6.82	$	380,959.47
	Engineering consultancy charges	0.15(0.15(CC + CC/0.4))	7.84	$	438,103.39
	Contingencies and other	0.2(0.15(0.15(CC + CC/0.4)))	12.02	$	674,828.11
	Total capital costs		100	$	5,624,186.00
Operating cost	Corn stover purchase/ grinding/transport	Based on 200 tons per day at $37.5 per ton for corn stover.	83.67	$/year	2,250,000
	Lactic acid/choline chloride	Adjusted for industrial-scale production	0.03	$/year	30,000.00
	Cellulase enzymes	Required for hydrolysis	0.1	$/year	75,000.00
	Saccharomyces cerevisiae yeast	Fermentation process	0.05	$/year	15,000.00
	Electricity consumption	Based on $0.160/kWh and an estimated power use of 1,512 kWh/day.	3.23	$/year	499,670.28
	Water consumption	$0.47/$m^3$ for 20 m^3/day over 300 operational days	0.18	$/year `	28,200.00
	Repair and maintenance of all equipment	≈ 1.5% of all other capital costs.	0.68	$/year	82,675.53
	Government taxes	≈ 1 % of all other capital costs.	0.46	$/year	56,241.86
	Workers' remuneration	≈2% of all other capital costs.	0.93	$/year	112,483.72
	Total operating costs		100	$/year	3,169,271.39
	Unit running cost	Total operating cost ÷ (50,000 L/day × 300 days)		$/L	0.21
Revenues	Bioethanol sales	50,000 liters/day × 300 days/year × $1.50/liter.		$/year	22,500,000.00
	By-product sales (CO_2, biomass)	CO_2 for beverages, and residual biomass for animal feed.		$/year	750,000.00
	Treated water reuse	Estimated savings from reusing water on-site		$/year	150,000.00
	Total revenue			$/year	23,400,000.00
	NET profit	Total revenue ($/year) – operating costs ($/year)		$/year	20,230,7280.6
	Payback period	Total Capital Costs ($) ÷ Net Profits ($/year)		years	2.78 years
	NPV	(cash flow at time t ÷$(1 + r)^t$) – Initial Investment		$	8,765,000.00

4.3. Key Cost Drivers, Production Economics, and Competitiveness of Bioethanol for E10 Blending

The ever-increasing cost of fossil fuels and the fact that Zambia relies on imported petroleum products necessitate alternative energy solutions. Bioethanol, derived from agricultural residues such as corn stover, presents a viable option for reducing fuel costs, enhancing energy security, and stimulating local economic development. This study evaluated the techno-economic feasibility of bioethanol production, highlighting key cost drivers, the cost per liter of bioethanol, the investment payback period, and the impact of E10 blending on Zambia's fuel pricing and economy, as well as the environmental impact.

4.4. Capital and Operating Costs

The total capital investment required for a bioethanol production plant with a 50,000-liter/day capacity was estimated at $5.62 million. **Figure 2** illustrates the percentage breakdown of capital investments for the bioethanol plant.

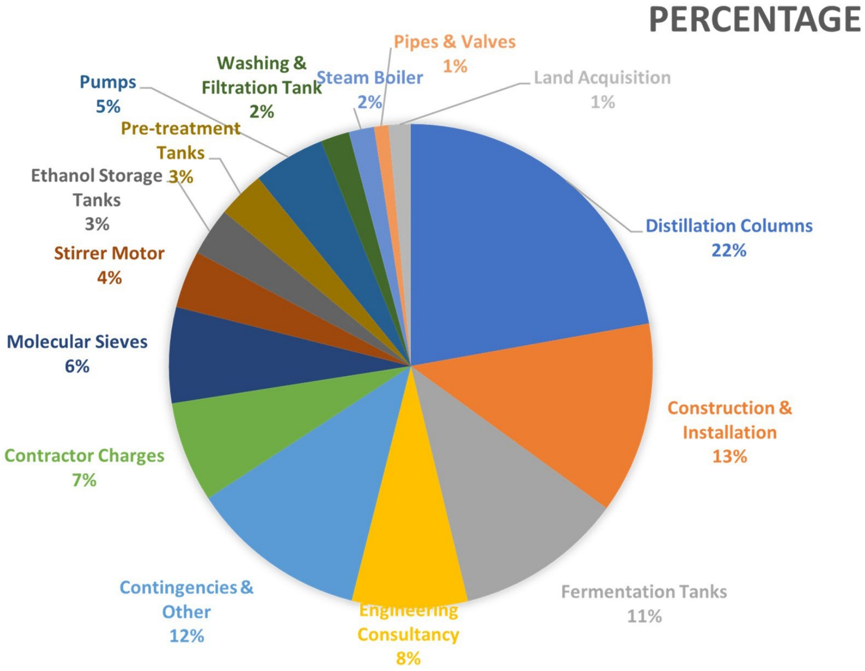

Figure 2. Percentage breakdown of capital investments for the bioethanol plant.

The most significant capital cost components were the distillation columns, which account for 22.49% of the total investment, followed by fermentation tanks (11.36%) and construction and installation (12.99%). Molecular sieves for dehydration contribute 6.49% to the total capital expenditure. These figures align with previous studies by [34], which found that distillation infrastructure remains one of the most cost-intensive elements in bioethanol production from lignocellulosic biomass.

Annual operating costs for the plant amounted to $3.17 million, with the largest expenditure being feedstock procurement and processing at $2.25 million per year (83.67% of total operating costs). Other significant costs included utilities such as electricity and water ($527,870.28 annually) and enzymatic hydrolysis, which accounted for $120,000 per year. Compared with the findings of [35], who reported enzyme costs as a major limitation in lignocellulosic ethanol production, the use of Deep Eutectic Solvents (DES) in this study significantly reduces pretreatment expenses, thereby lowering overall processing costs.

4.5. Cost per Liter and Payback Period

The cost of producing one liter of bioethanol was calculated at $0.21, making it highly competitive when compared to conventional production methods. Studies by [36] indicated that bioethanol production from agricultural residues typically ranges between $0.35 and $0.50 per liter, demonstrating the economic advantage of the DES pretreatment method used in this study. Revenue from ethanol sales was estimated at $22.5 million per year, based on a selling price of $1.50 per liter, while by-product sales (CO_2, biomass, and treated water) can contribute an additional $900,000 annually. With a net annual profit projected to be $20.23 million, the payback period for the investment was estimated at 2.78 years, significantly shorter than the 4 - 7-year payback period reported by [37] for traditional lignocellulosic bioethanol plants. The reduced payback time highlighted the financial viability of this approach, making it attractive to investors and policymakers. **Table 3** shows a concise sensitivity-analysis table summarizing how ±20% changes in key inputs shift the NPV and PB.

Table 3. Sensitivity analysis table, impact of ±20% variation in key inputs.

Variable	Change	NPV (USD)	Payback period (Years)
Ethanol selling price	+20% ($1.80/L)	$13,000,000	2.10
	−20% ($1.20/L)	$4,200,000	4.10
Feedstock cost (per ton)	+20%	$7,700,000	3.35
	−20%	$9,800,000	2.32
Capital cost	+20%	$6,400,000	3.30
	−20%	$11,100,000	2.20

4.6. Competitiveness and Effect on Fuel Price

The current gasoline retail price in Zambia stands at $1.1724 per liter. With the introduction of E10 blending, the projected pump price for blended fuel was estimated to be $1.0762 per liter, reflecting an 8.2% cost reduction. This price advantage is crucial in making fuel more affordable for consumers. Studies by [38] also confirm that ethanol blending leads to reduced fuel costs and improved energy security, particularly in economies reliant on fuel imports. In terms of fuel substitution, the adoption of E10 blending can displace approximately 44.5 million liters of gasoline annually, reducing Zambia's petroleum import bill. This shift aligns with global trends, as noted by [39], who highlighted that ethanol blending policies in emerging economies have successfully reduced fuel costs and foreign exchange expenditures.

It is necessary to recognize possible logistical and policy-related risks that could affect the payback period, even though the techno-economic analysis shows financial viability. Supply chain disruptions, such as a lack of baling equipment, seasonal transportation limitations, or problems with the road infrastructure, can raise the cost of handling feedstock or cause delays in operations. On the policy side, unclear fuel pricing rules, ethanol blending requirements, or incentives for biofuel investors could all slow market demand or postpone revenue realization. These risks could cause the anticipated payback period to be longer than the 2.78-year projection, especially if capital recovery is linked to shaky policy frameworks or inadequate infrastructure. To protect the project's financial performance, it will be essential to proactively address these factors through stakeholder engagement and supportive national bioenergy policies.

4.7. Economic and Policy Implications

Bioethanol production has the potential to stimulate Zambia's economy through job creation, value addition, and industrial development. The construction and operation of bioethanol plants can generate employment across multiple sectors, including agriculture, manufacturing, and transportation [40]. Farmers can benefit from increased demand for corn stover, providing an additional revenue stream and supporting rural livelihoods. The economic impact can extend to reducing Zambia's dependence on imported petroleum, easing pressure on foreign currency reserves. By displacing 44.5 million liters of gasoline annually, the country will achieve significant foreign exchange savings, which can be redirected to other critical sectors such as healthcare and infrastructure development [41]. Beyond cost competitiveness, bioethanol production offers broader economic and policy benefits. The displacement of fossil fuel imports can lead to substantial foreign exchange savings, ensuring greater energy security for Zambia. Additionally, the establishment of bioethanol plants can create employment opportunities across the agricultural supply chain, industrial processing, and logistics sectors.

4.8. Environmental Impact of E10 on Gasoline Combustion

The adoption of bioethanol-gasoline blends, such as E10, presents a potential strategy for reducing greenhouse gas (GHG) emissions, improving air quality, and enhancing energy security. Bioethanol, derived from renewable biomass, is of a lower carbon intensity than conventional gasoline due to its biogenic carbon cycle [42]. Studies indicate that bioethanol blending displaces high-carbon aromatics in gasoline, contributing to emission reductions [43]. Several countries are reporting lower CO_2 emissions, reduced reliance on petroleum imports, and improved air quality following the implementation of bioethanol blending policies [44].

4.9. GHG Emission Reductions and Climate Mitigation

Zambia's gasoline consumption in 2023 was recorded at 445,044.58 metric tons, with estimated CO_2 equivalent (CO_2e) emissions calculated at 1,366,286.86 metric tons (Mutemi, 2022). The introduction of E10 was projected to reduce these emissions to 1,229,658.17 metric tons, representing an annual reduction of 136,628.69 metric tons, or approximately 10%. The extent of this reduction aligns with Zambia's climate mitigation commitments, suggesting bioethanol's potential role in national carbon reduction strategies [45].

The reduction in emissions is attributed to bioethanol's renewable nature. Unlike fossil-based fuels, bioethanol is produced from biomass, which absorbs CO_2 during plant growth, partially offsetting emissions from combustion. Life-cycle analyses indicate that corn-based bioethanol can achieve up to a 40% reduction in GHG emissions compared to gasoline [46]. Furthermore, E10 blending has been proven to decrease fuel carbon intensity to 43.4 g/MJ or lower, primarily due to the displacement of gasoline's high-carbon components (Higgins *et al*., 2023). Since bioethanol combustion is considered carbon-neutral, blends such as E10 and E15 contribute no net additional CO_2 emissions from the bioethanol component [47].

4.10. Air Quality and Public Health Implications

Apart from GHG reductions, bioethanol blending is linked to improved air quality through the reduction of harmful pollutants, including carbon monoxide (CO), particulate matter (PM), and volatile organic compounds (VOCs) [48]. These pollutants are known to be contributors to urban air pollution and respiratory illnesses. Several studies suggest that the use of bioethanol-blended fuels results in lower concentrations of these pollutants, especially in densely populated areas. Countries with established bioethanol blending programs have reported measurable declines in respiratory diseases associated with poor air quality, suggesting potential public health benefits from bioethanol adoption [49].

4.11. Economic and Energy Security Considerations

Bioethanol blending has always been associated with economic and energy security benefits. By reducing total emissions, bioethanol adoption can lead Zambia to participate in carbon credit markets, generating additional revenue and attracting investment into renewable energy sectors [50]. Some countries have successfully leveraged carbon credit mechanisms to offset bioethanol production costs and stimulate biofuel industry growth [51]. The economic benefits extend to job creation, industrial development, and value addition in agriculture. The establishment of bioethanol plants could create employment across multiple sectors, including agriculture, manufacturing, and transportation [52]. Increased demand for bioethanol feedstocks, such as corn stover, can provide an additional revenue stream for farmers, with potential positive effects on rural economies [53]. Furthermore, bioethanol blending could reduce Zambia's reliance on imported petroleum, thereby easing pressure on foreign currency reserves. The displacement of an estimated 44.5 million liters of gasoline annually could translate into significant foreign exchange savings, with potential implications for national resource allocation [54].

4.12. Policy and Sustainability Considerations

The successful integration of bioethanol into Zambia's fuel market may require supportive policies, infrastructure investment, and public awareness initiatives. Studies indicate that countries with well-developed bioethanol programs often implement policy frameworks that incentivize bioethanol production and distribution [55]. The long-term sustainability of bioethanol blending could depend on factors such as feedstock availability, production efficiency, and market competitiveness. Research on second-generation bioethanol derived from agricultural residues suggests additional environmental benefits compared to first-generation bioethanol, indicating potential avenues for further investigation [56].

5. Conclusions

The study provided a comprehensive techno-economic analysis of bioethanol production from corn stover in Zambia, examining its financial viability, environmental impact, and potential benefits for energy security. The outcomes demonstrated, through the integration of cost analysis, process optimization, and environmental assessments, that bioethanol could serve as a sustainable alternative to fossil fuels. The conclusions highlighted key takeaways from the study, while the recommendations outlined strategic actions necessary for successful implementation and long-term sustainability of bioethanol production in Zambia.

The study confirmed that bioethanol production from corn stover in Zambia was both economically and environmentally viable. The cost of production, at \$0.21 per liter, made it competitive compared with fossil fuel alternatives, with a short payback period of 2.78 years, making it an attractive investment. The implementation of E10 fuel blending was projected to lower fuel prices, with the pump price of E10 estimated at \$1.0762 per liter, an 8.2% reduction from the gasoline price of \$1.1724 per liter, making fuel more affordable for consumers and industries. Furthermore, bioethanol adoption can contribute to environmental sustainability by reducing greenhouse gas emissions by 10% and lowering carbon monoxide and particulate matter levels, which can improve air quality and public health. The transition to E10 was expected to cut CO_2e emissions by approximately 136,628.69 metric tons annually, aligning with Zambia's climate action commitments. The shift to bioethanol can further enhance energy security by reducing reliance on imported petroleum while generating additional income streams for farmers and stakeholders in the biofuel industry. These findings reinforced the potential of bioethanol to drive both economic growth and environmental improvements in Zambia, aligning with global efforts for cleaner and more sustainable fuel alternatives.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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