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Process Modelling and Techno-Economic Analysis of Rice Husk Valorisation to Gasohol

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Abstract

Nigeria's reliance on fossil fuels can be reduced by adopting gasohol, a blend of gasoline (petrol) and bioethanol, which is being developed in response to the growing global demand for sustainable, clean energy. In addition to depleting the country's foreign reserves, conventional petroleum exacerbates the climate change dilemma, causing environmental risks like rising temperatures, flooding, and greenhouse gas emissions. Even where fossil fuels are unavoidable, blending bioethanol with gasoline improves combustion, reducing tailpipe pollutants and offering a practical mitigation strategy. Although commercial-scale bioethanol production has extensively used traditional food crops such as sugarcane, corn, and wheat, these feedstocks have presented a fundamental sustainability problem — they compete directly with human food supply chains, threaten national food security, and drive inflationary pressure on crop prices, making them unreliable for long-term bioethanol-gasohol production.

This study, therefore, probes the energy economy evaluation of rice husk for gasohol production using a comprehensive process model developed in Aspen HYSYS v.10. It involves a steady-state simulation of dilute-acid pre-treatment, enzymatic hydrolysis, co-fermentation, glycerol-based extractive distillation and dynamic simulation of 10:90 bioethanol-gasoline blending using ratio controllers for maintaining consistency with the pre-set ratios. It also includes a rigorous deterministic financial model developed by CAPCOST_2017 and Uncertainty and Risk Analysis, which uses Monte Carlo simulation to determine the probability of profitability owing to a ±20% variance in raw material prices and other parameters.

The plant produced 9.75 million litres of 99.96% wt pure bioethanol from 20,805 tons of milled rice husks, yielding 469litres/ton in 8,322 hours annually. The Fixed Capital

Investment (FCI) of the proposed plant, incorporating a 2-year construction phase, a 20-year operational economic life, and a 10-year straight-line depreciation schedule, is $3.09 million (representing a capital intensity of $0.32/litre), with a unit production cost of $0.39/litre. At a proposed selling price of $0.55/litre, the plant is projected to generate $5.38 million revenue annually, $1.51 million profit before tax and $1.06 million profit after tax at a 30% tax rate.

Keywords: Techno-Economic Analysis, Lignocellulose Biomass, Bioethanol, Extractive Distillation, Process Simulation, E-10 Gasohol

Introduction

Concerns about the depletion of fossil fuel supplies and the pollution they cause are spreading worldwide, drawing attention to alternative energy sources, particularly renewable energy sources [1]. Bioethanol, which is manufactured from biomass, has emerged as a promising alternative to fossil fuels, particularly for transportation [2]. It is a renewable and environmentally friendly fuel produced from various biomass sources, including agricultural residues, forest waste, municipal solid waste, and energy crops [3]. The combination of a supportive framework and research investment in the US has propelled the US ethanol industry to become one of the world's largest [4]. Brazil, also considered a global leader in bioethanol production, accomplished this feat due to abundant land resources and a favourable climate for sugarcane cultivation, the primary biomass used for bioethanol production [5]. The established sugarcane industry in Brazil is a major supplier of bioethanol fuel in the country's automotive industry [6].

The utilisation of edible biomass, such as corn, sugarcane, and wheat, for bioethanol production has raised concerns regarding food security, resource use, and environmental sustainability [7]. To counter these challenges, attention has shifted to lignocellulosic biomass because it is cheap and abundant and addresses a critical food-energy dilemma [8]. It is composed of complex and recalcitrant polymers, namely cellulose, hemicellulose, and lignin, which require pretreatment, hydrolysis, and fermentation to be converted into ethanol [9]. However, these processes are challenging owing to the variability in biomass biochemical composition, lignin's resistance to enzymatic degradation, and fermentation inhibition by toxic compounds generated during pretreatment.

Rice Husk is the hard, inedible layer that coats the paddy grain [10]. It is a product of mechanical milling and accounts for approximately 20% of the total weight of rough rice [11]. Therefore, for every ton of harvested rice, 280 kg of rice husk is produced, indicating its viability and sustainability as a fuel [12]. It is generally composed of cellulose (50%), lignin (25–30%), silica (15–20%), and moisture (10–15%). The bulk density of rice husks ranges from 90–150 kg/m^3 [13].

Currently, sugar and starch crops account for the largest share of global bioethanol production. The United States of America holds the top position in bioethanol production from corn grain, while Brazil is the second largest producer, utilising sugarcane as feedstock [14]. However, using food crops for bioethanol production is unsustainable owing to food-fuel competition [15], rising food prices, and the high energy, water, and land requirements of intensive farming practices [16].

Owing to these challenges, it is important to achieve the efficient use of lignocellulose-based feedstocks for bioethanol production. There are a few valorisation pathways for 2G feedstocks (rice husks) that have been implemented, but there is a lack of comprehensive process designs for transforming rice husks into gasohol [17]. The objectives of this study include designing unit operations in Aspen HYSYS to model the conversion processes to bioethanol, determining the design parameters for a continuous distillation unit to produce fuel-grade bioethanol for ethanol-gasoline blending, determining how a ratio-based system can be modelled to simulate and maintain the specified ethanol: gasoline ratio in dynamic blending under unpredictable flow, and determining the effect of different market scenarios on economic performance indicators.

Several studies have illustrated the possibility of producing bioethanol from agricultural residues. In a study by [18], the bioethanol yield from the conversion of corn stover was 0.38 g/g using a combination of alkaline pretreatment and enzymatic hydrolysis. In another investigation, [19] observed that pretreating corn stover with an alkali and *Saccharomyces cerevisiae* increased the bioethanol yield to 0.26 g/g. These findings indicate that corn stover is a viable feedstock when suitable conversion methodologies are employed. [20] In their study, they applied fungal isolates to a pretreated rice husk substrate. They observed that the pretreatment process reduced the lignin and hemicellulose content and increased cellulose exposure. *Aspergillus niger* and *Aspergillus flavus* were then introduced together to the cellulose during the hydrolysis stage to increase the concentration of reducing sugars. Likewise, for fermentation, *Pichia kudriavzevii* and *Saccharomyces cerevisiae* were applied both individually and in combination. Fourier-transform infrared spectroscopy (FTIR) analysis showed a high ethanol content of 68%.

[21], developed a small-scale production facility to optimise bioethanol yield from cassava peels. They conducted experiments to optimise the fermentation temperature and time, which significantly affected the bioethanol yield. They observed high glucose production and efficiency after 72 hours of fermentation at 30°C. This indicates that the established conditions improved both the quality and yield of bioethanol from cassava peels.

Bioeconomy Theory

The conceptual framework for this study is based on bioeconomy theory and the biorefinery concept. The former describes a system in which renewable resources, such as biomass, are sustainably managed to produce food and energy. It refers to a set of actions aimed at delivering sustainable solutions based on biomass to create value [22]. The set of actions for value addition to biological resources, such as crops, forest reserves, aquatic (algae), and waste streams, involves the application of scientific and technological knowledge [23], as shown in Figure 1. It also involves know-how in biotechnology, which can develop processes that create value (bioethanol, biopharmaceuticals and industrial enzymes) [24], and ameliorate societal challenges, ranging from food and feed production to bioenergy, while ensuring that our ecological assets are preserved [25].

Biorefinery Concept

The idea relates to the processing plant's ability to convert biomass feedstock into a range of useful products. This process is characterised by integration of several processes and knowledge from other disciplines (chemistry, agronomy, engineering, etc.) designed to work together in a coordinated system to produce multiple outputs ranging from energy (biofuels, biogas and heat), materials (bioplastics and fibres) and chemicals (pharmaceuticals & solvents) [26].

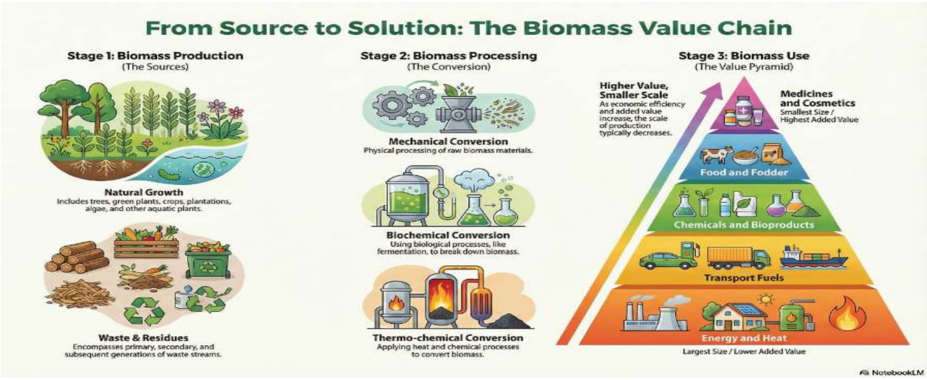

Figure 1: Biomass-based economy Concept [27]

Biorefinery is categorised into (a) Feedstock (e.g., whole food crop, lignocellulose, or marine). (b) Technology type (e.g. bio- or thermo-chemical biorefinery), (c) technology status (e.g., conventional or advanced biorefinery, or 1st /2nd generation biorefinery and (d) Main (intermediate) product produced (e.g., sugar, syngas or lignin biorefinery) [28]. Its primary objective is to reduce dependence on fossil-based energy services. However, this can only be achieved if biorefinery products (e.g., biochemicals, automotive fuels, fuels for heat and electricity generation) have a market presence. Renewable biofuels and value-added products generated from lignocellulosic biorefineries play a significant role in fostering a sustainable economy [29].

Methodology

For simulation purposes, rice husk was selected as the feedstock because of its high cellulose and hemicellulose content, regional abundance and non-competition with food. The key process chemical inputs are dilute sulphuric acid for the pre-treatment and hydrolysis stages, commercial cellulase enzymes for the further enzymatic breakdown of cellulose into fermentable sugars, and engineered *Zymomonas mobilis* for fermentation. Process simulation was conducted using Aspen HYSYS v10, with the Non-Random Two Liquid (NRTL) model selected as the property package for its ability to model thermodynamic phases. Aspen Economic Analyser was used for equipment sizing, and the mapping outcomes were exported to CAPCOST_2017 for manufacturing cost calculations. Also, key profitability indicators, including Net Present Value (NPV), Discounted Cash Flow Rate of Return (DCFROR), and Discounted Payback Period (DPBP), were calculated. Water, electricity, and low-pressure steam were considered conventional and crucial inputs for plant operations. Figure 2 shows the block diagram of the general steps used in the research.

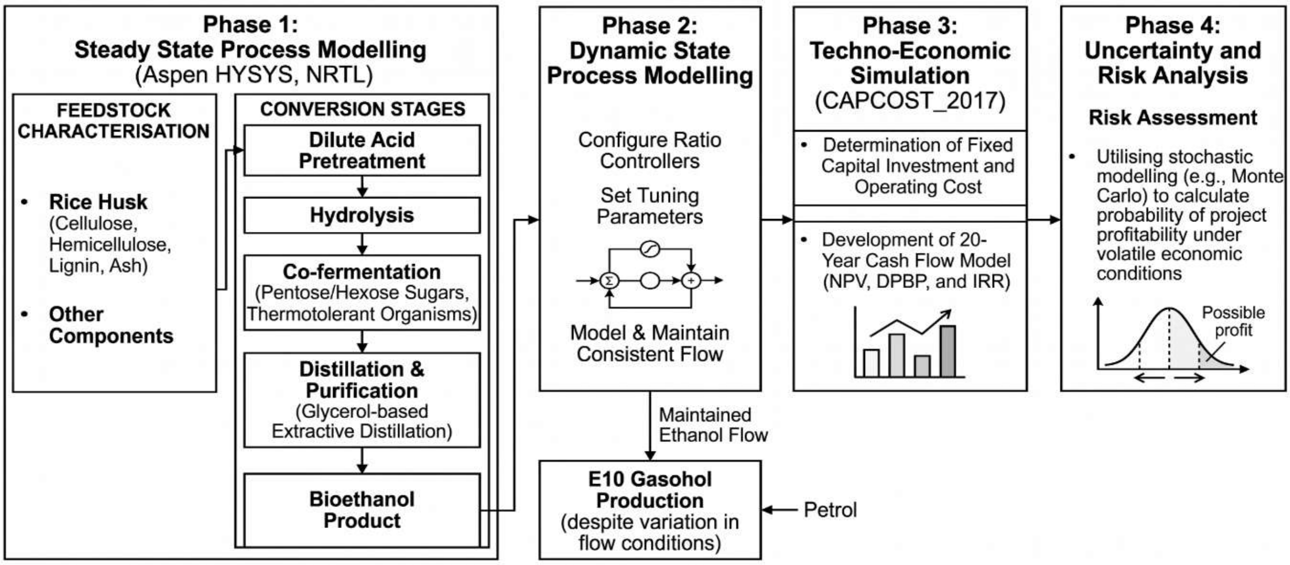

Figure 2: Block diagram of the methodology adopted for the study

Feedstock Characterisation

Cellulose, hemicellulose, lignin and moisture content, which make up the composition of rice husk, were obtained from the literature, and the values were entered into the Aspen HYSYS components list. Table 1 presents the components considered in the study, and Table 2 presents the feedstock composition entered into Aspen HYSYS.

Table 1. Components used in the steady-state simulation.

Component	Chemical Formula	Process Application
Acetate	$C_2H_4O_2$	The Acetyl groups present in the hemicellulose polymer
Acetic Acid	CH_3COOH	Acetate hydrolysis is a by-product of fermentation
Carbon-Dioxide	CO_2	Fermentation Product
Cellobiose	$C_{12}H_{22}O_{11}$	Enzymatic Hydrolysis Product
Cellulose	$(C_6H_{10}O_5)$ n	Feedstock
Ethanol	C_2H_5OH	Fermentation Product
Furfural	$C_5H_4O_2$	By-product of hydrolysis
Glucose	$C_6H_{12}O_6$	Hydrolysis Product and yeast growth input.
Glycerol	$C_3H_8O_3$	Fermentation by-product
Hemicellulose	$(C_5H_8O_4)$ n	Feedstock
Lignin	$(C_{31}H_{34}O_{11})$ n	Feedstock
Oxygen	O_2	Fermentation by-product
Sodium sulphate	Na_2SO_4	Neutralisation Product
Sodium-Hydroxide	$NaOH$	Neutralisation Reactant
Sulphuric acid	H_2SO_4	Catalyst (Pretreatment and Hydrolysis)
Water	H_2O	Input for hydrolysis, mixing and washing
Xylitol	$C_5H_{12}O_5$	Fermentation by-product

Xylose	$C_5H_{10}O_5$	Hydrolysis product
Zymomonas mobilis	$CH_{1.8}O_{0.5}N_{0.2}$	Fermentation Bacteria

Table 2. Feedstock Composition

Component	Range (wt.%)	Input Value (wt.%)
Cellulose	32.1-48.6	47.8%
Hemicellulose	27.1-38.7	36.5%
Lignin	5.3-17	13.2%
Acetyl	2-5%	2.5%
Total		100

Source:(Canizares et al., 2020).

Steady-State Modelling

Dilute acid pretreatment, enzymatic hydrolysis, co-fermentation, beer and rectification distillation and glycerol-based extractive distillation conversion stages were modelled with unit operations in steady-state mode within Aspen HYSYS.

Dynamic-State Modelling

The blending process of petrol and bioethanol was modelled using unit operations in dynamic state mode within Aspen HYSYS. This method is crucial for ensuring that the blend quality and product specification (E10: 10% ethanol, 90% petrol) are consistent. This is achieved by ensuring that the preset 0.11 volumetric ratio is maintained, as would be expected under real-world operating conditions.

Process Flow Description (Steady-state)

2500 kg/hr of water mixed with milled rice straw enters the mixer and is slightly heated. The mash then flows into the pre-treatment reactor, where cellulose and hemicellulose are hydrolysed into glucose and xylose, respectively (Figure 3a). The conversion rates are 10% and 90%, respectively. The unreacted cellulose and xylose stream flows into the hydrolysis reactor after neutralisation. The hydrolysis reactor converts the remaining cellulose into glucose in the presence of cellulase (Figure 3b). The glucose and xylose solution flows into the fermentation reactor, where engineered *Zymomonas mobilis*, using a co-fermentation approach, converts the sugars into ethanol, evolving CO_2 (Figure 3c). The beer produced in the fermentation reactor is distilled in the first distillation column, also called the beer column. The hydrous product is further distilled in the rectification column. The desired purity is achieved by using glycerol as an entrainer to break the ethanol-water azeotrope. Glycerol is then recovered from the glycerol-recovery column and recycled (Figure 3d).

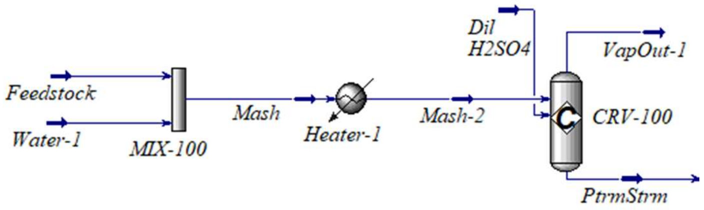

Figure 3a: Process Flowsheet of the Pretreatment Stage

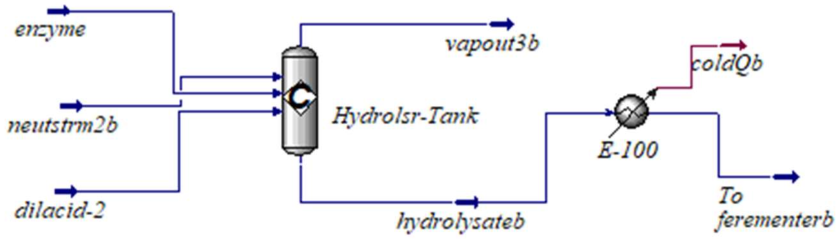

Figure 3b: Process Flowsheet of the hydrolysis stage

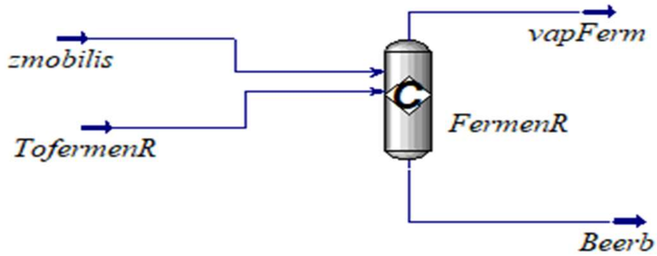

Figure 3c: Process flowsheet of the fermentation stage

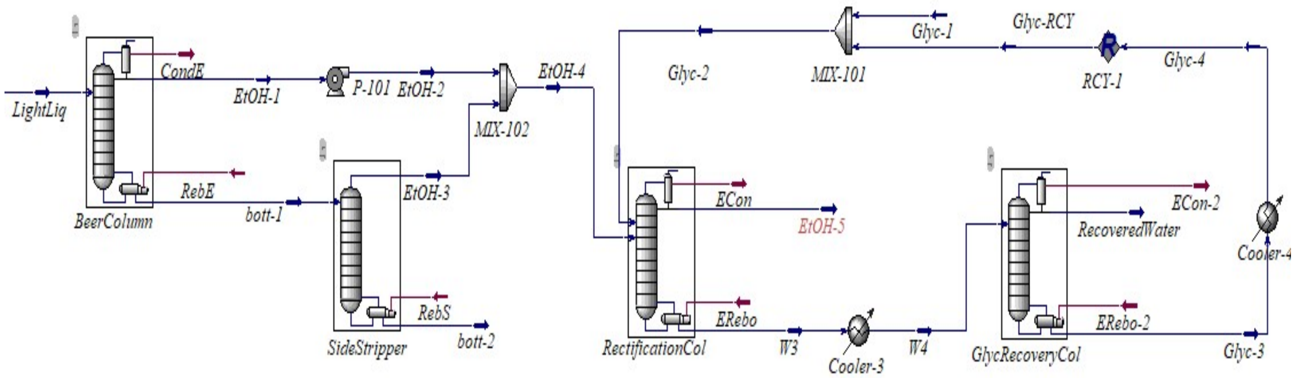

Figure 3d: Process flowsheet of the multistage distillation and glycerol recovery stage.

Blending Process Description (Dynamic-state)

The ethanol and gasoline stream is passed through valves into a blender. The ratio controller is attached to the valve end connected to the ethanol stream, as shown in Figure 4. The system receives the ethanol flow signal, then regulates the gasoline valves' opening and closing. The established volumetric ratio for the E10 blend, comprising 10% ethanol and 90% gasoline, is set to 0.111, and the control system is designed to maintain this ratio consistently.

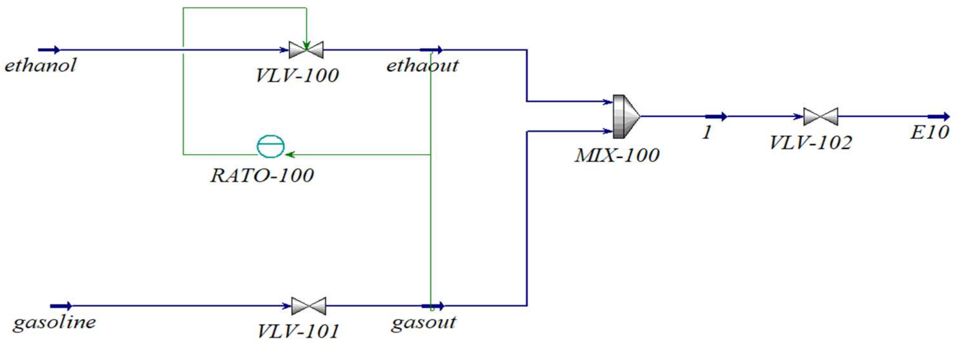

Figure 4: Process flowsheet of the dynamic blending of ethanol and gasoline.

Techno-economic Simulation

A techno-economic simulation of the bioethanol plant was conducted using the results of Aspen HYSYS steady-state and dynamic modelling in CAPCOST_2017. This is because CAPCOST_2017 is useful for estimating the cost of chemical process equipment, as well as capital and operating costs, based on equipment sizing, material selection, and process conditions derived from steady-state and dynamic simulations. The Chemical Engineering Plant Cost Index (CEPCI) adjusts equipment pricing based on current economic conditions. For this study, 800 was selected to correspond to the most recent available index for the year. Key financial inputs were defined to perform the economic analysis of the bioethanol and gasohol blending process. These inputs form the framework for equipment costing, operating expense estimation, and investment analysis. Tables 3 and 4 present the economic assumptions used in CAPCOST_2017 to determine the plant's profitability.

Table 3: Input parameters for Project Economics Evaluation.

Item	Description
Working time (hrs)	8322
Discount rate (%)	10

Proposed product(petrol) price ($/L)	0.66
Currency Exchange (NGN/$)	1500
Tax (%) /Interest (%)	30 /10
Proposed plant life (Yrs)	20
Depreciation type	Straight line
Depreciation duration (Years)	10
Construction Period (Years)	2

Table 4: Input Unit prices of raw materials and utilities.

	Materials	Price	Unit
Raw Materials	Enzyme (Cellulase)	0.314	$/kg
	Milled Rice Husk	0.09	$/kg
	Sodium Hydroxide	0.076	$/kg
	Sulfuric Acid	0.017	$/kg
	Z. Mobilis/Yeast	0.062	$/kg
Utility	Cooling Water (303K to 318K)	0.3781	$/GJ
	Low-Pressure Steam (5 barg, 160°C)	2.03	$/GJ
	Electricity	0.15	$/kWhr

Source: Adapted from [6], CAPCOST_ 2017)

Determination of Economic Indicators

NPV is an economic indicator used for assessing the potential profitability of a project; NPV ≥ 0 indicates acceptance, whereas NPV < 0 indicates rejection [32]. [33] express it as;

$$NPV = \sum_{y_r=0}^{n_p} \frac{CF_y}{(1+d)^{y_r}} \qquad (1)$$

where y_r, n_p, d, and CF_y are the plant year, useful life, discount rate, and after-tax cash flow, respectively.

The after-tax cash flow, according to [34] is expressed as

$$CF_y = [R - (COM_d + d)]\,(1 - t) + d_p \qquad (2)$$

R, t, and d_p denote revenues from sales of products or by-products, tax and depreciation, respectively.

DPBP refers to the time spent to recover the invested capital in a project. [35] expressed the relationship as,

$$DPBP = Y_n + ABS\left(\frac{C_d}{C_p}\right) \qquad (3)$$

Y_n is the last year of discounted negative cumulative cash flow; C_d is the negative value of the cumulative discounted cash flow, and C_p is the present value *PV* after the last year of negative cash flow (absolute cumulative cash flow).

DCFROR represents the discount rate at which the *NPV* of all cash flows from an investment equals zero (Towler & Sinnott, (2013) express it as,

$$NPV = \sum_{i=0}^{N} \frac{C_t}{(1+r)^t} = 0 \quad (4)$$

Risk Simulation

A Monte-Carlo Simulation (N=1000 iterations) was conducted to account for the combined effects of multiple uncertain variables and market volatility on the performance of NPV, DCFROR and DPBP. This stochastic modelling technique used probability distributions for key inputs (material price, ethanol sale, working capital, tax rate)

RESULTS AND DISCUSSION

Overall Mass Balance

The material balance analysis is shown in Table 5; the total mass flow of inlet streams is 6636 kg/hr, and the outlet flow stream is 6637 kg/hr. At the bioethanol-gasoline blending stage, ethanol and gasoline are blended to produce E10 fuel. Their mass flow rates are 145.5 kg/hr and 1140.0 kg/hr, respectively, producing 1285.5 kg/hr of E10. The overall relative imbalance is 0.013%, confirming mass conservation across all process points. The minimal deviation is within the limits of steady-state simulation.

Overall Energy Balance

The total energy flow of inlet streams and outlet streams is 5.586e+7 kJ/h each, resulting in an absolute and relative energy imbalance of -0.0006e+7 kJ/h and 0.01%, respectively, as shown in Table 6. Similarly, in the gasohol blending stage, the total inlet and outlet streams are −3.4645e+6 kJ/hr, -3.4645e+6 kJ/hr, respectively, resulting in an absolute imbalance of -1.99e-13 kJ/h and a relative imbalance of 0.00%. These results indicate that all the unit operations were accurately modelled for the conversion stages with thermodynamic consistency.

Process Performance Analysis

A bioethanol fuel-grade purity of 99.96% wt was achieved from steady-state simulations of unit operations. The final product achieved a flow rate of 925 kg/hr, and the beer column distilled 953.9 kg/hr of beer. At the pretreatment phase, 90% of both the hemicellulose and lignin were converted and solubilised, respectively. The process efficiency and ethanol yield are shown in Table 7. 1961 kg/hr of fermentable sugar were released during the hydrolysis stage, compared to the theoretical amount of 2364 kg/hr, suggesting an 83% hydrolysis efficiency. The combined product of the first and second stages of distillation is 953.59 kg/hr.

Table 5. Summary of flowsheet-wide energy balance

Section	Inflow Streams	Mass Flow (kg/hr.)	Outflow Streams	Mass Flow (kg/hr)
Upstream Process	Water-1	2,500.00	To Blending: Ethanol Stream	145.5
	Feedstock	2,500.00	Other Intermediates	6,491.84
	Dil H_2SO_4	1,250.00		
	Other Inputs	386.3		
	Subtotal Inlets	6,636.30	Subtotal Outlets	6,637.34
Gasohol Blending	Ethanol Stream	145.5	E10 Gasohol	1,285.00
	Gasoline	1,139.50		
	Subtotal Inlets	1,285.00	Subtotal Outlets	1,285.00
Total Process	All Inlets	7,921.30	All Outlets	7,922.34
	Absolute Imbalance	1.04 kg/hr	Relative Imbalance	0.013%

Table 6. Summary of flowsheet-wide energy balance.

Process Section	Inlet Stream (kJ/h)	Outlet stream (kJ/h
Upstream Process	5.86×10^3	5.86×10^3
Gasohol Blending	-3.465×10^6	-3.465×10^3
Overall Process	5.51×10^7	5.51×10^7
Relative Imbalance		0.00%

In comparison to the theoretical value of 1208 kg/hr, the fermentation efficiency is 78.93%. At the rectification stage, 925 kg/hr of fuel-grade bioethanol was distilled, while the fermentation theoretical value is 1208 kg/hr; however, when compared with the final output, the overall process efficiency is 76.53%, and the actual yield is 469 litres per ton.

Table 7. Process Efficiency and Yield Analysis.

Item	Amount	Unit
Bioethanol Yield (Concentrated/Beer)	469/483.44	Litre/Ton
Bioethanol Production Rate (Concentrated/Beer)	925.1/953.59	kg/hr.

	Theoretical	Study
Sugar Content (kg/hr.)	2364	1961.96
Hydrolysis Efficiency	0.83	
	Theoretical	Study
Ethanol Content (Beer)(kg/hr.)	1208	953.59
Theoretical Efficiency	78.9%	
	Theoretical	Study
Ethanol Yield: Beer (Litre/Ton)	613	483
Yield Efficiency	78.8%	
	Theoretical	Study (Conc)
Ethanol Content(kg/hr.)	1208.84	925.1
Overall Process Efficiency	76.5%	

Technoeconomic Analysis

Equipment Cost, Utility Summary and Analysis

The cost breakdown presented in Table 8 includes the purchase-equipment cost, the bare module cost, and the base bare cost of 35 equipment units. The bare module cost is $ 1.91 million, while the base bare module cost is $ 1,827,900. These values reflect the direct equipment cost and the indirect expenses relating to the equipment installation. The cost distribution shows that the capital expenditure is concentrated in three primary equipment groups, which together account for 84.7% of the total bare module cost. The storage tank accounts for 34.3% of the bare module cost. The seven units of fixed-roof storage tanks represent the single largest capital outlay of $ 656,600, reflecting the high volumetric capacity required for continuous operation. The distillation towers account for 32% of the bare module cost. The four sieve towers require a bare module investment of $11,600. The data highlights a significant variance between the base bare module cost ($380,200) and the actual bare module cost. The premium is driven by stainless steel and stainless steel-clad material specifications. Heat Exchangers account for 18.4% of the bare module cost. The eleven double-pipe and multiple-pipe exchangers cost $352,000, reflecting the high thermal demand of the process, particularly the heating duties for the pretreatment feed and the reboilers in the multi-distillation stage sequence.

Plant Profitability Analysis

The cost of manufacturing was determined using calculated values of operating labour cost C_{OL}, utility cost C_{UT}, waste treatment cost $C_{WT,}$ and raw material cost C_{RM}. It is given by the expression [34].

$$0.18*FCI+2.73*C_{OL}+1.23(C_{UT}+C_{WT}+C_{RM}) \quad (5)$$

The input parameters listed in Table 9 were used to calculate the COM_d. Table 10 displays the estimated value using Equation 5. The calculated production cost is $0.50/kg ($0.39/litre), and is the cost before distribution and retail mark-up. From Table 11, $5.39 million in revenue was generated at a proposed sale price of $0.55 per litre. The profit before tax is $1.51 million, and the profit after tax is $1.06 million. A petrol price of $0.61 per litre serves as a benchmark for comparative reference to showcase the profitability of the bioethanol plant and the viability of gasohol blending.

Table 8. Equipment Structure, Cost and Specifications

Equipment Group	Type	Unit	MOC	PEC ,000($)	BMC ,000($)	BEC ,000($)	BBM ,000($)
Centrifuge	CTF	1	–	25.2	39.5	25.2	39.5
Heat Exchangers	DP/MP	11	CS /CS	107.06	352.5	107.06	352.5
Filters	LF	1	–	49.2	81.2	49.2	81.2
Mixers	TB	3	–	34.2	47.1	34.2	47.1
Pump	CTF	3	CS	30.6	78.7	19.8	64.0
Storage Tanks	FR	7	–	596.4	656.6	596.4	656.6
Towers	SV	4	SS /SSC	373.8	611.6	181.6	380.2
Vessels	HRZ	5	CS	15.0	45.2	15.0	45.2
Total				1231.46	1912.4	1028.46	1666.3

Source: CAPCOST_2017 calculations based on Aspen HYSYS mapping and sizing results.
Centrifugal (CTF), Double Pipe (DP), Multiple Pipe (MP), Leaf (LF), Turbine (TB), Fixed Roof Tank (FRT), Sieve (SV), Carbon Steel (CS), Stainless Steel (SS), Stainless Steel Clad (SSC) and Horizontal (HRZ)

Table 9. Capital Composition for determining COM_d

Item	Amount ($)
C_{RM}	2,173,090
C_{UT}	173,000
C_{OL}	155,500
C_{WT}	Nil

Table 10. Determination of COM_d

Description	Units	Amount
Salvage Value[1]	$	309,000

[1] The salvage value was calulated as a percentage of FCIL

Working Capital	$	574,000
FCI	$	3,090,000
C_{OM}	$	3,871,071
Unit Cost	$/kg ($/L)	0.50 (0.39)

Table 11. Pricing Model and Revenue

Description	Value	Unit
Product (Ethanol)	9,756,463.88	L
Base Price (Petrol)	0.61	$/L
Proposed Sale Price	0.55	$/L
Revenue	5,388,495.00	$
Exchange Rate	1500	N/$
Tax Rate	30%	
Profit before Tax	1,518,006.14	$
Profit After Tax	1,062,604.30	$
Subsidy	0.00%	

Economic Performance Analysis

The discounted cash flow analysis over the 20-year project life yields an NPV of $4.92 million at 10% discount rate, demonstrating significant positive value creation. The DCFROR is 27.83%, exceeding the 10% discount rate, indicating robust profitability. The DPBP is 6 years, meaning the initial investment will be recovered within approximately one-third of the project's economic life. These financial indicators confirm that the bioethanol production from rice husk is economically viable and attractive under Nigerian market conditions, even without government subsidies or incentives.

Probabilistic Risk Analysis

NPV Probability Distribution

From Figure 5, the expected mean NPV is $3.78 million, and the median is $3.88 million, indicating a consistent central tendency towards value creation despite market volatility. Furthermore, 98.4% of scenarios yield a positive NPV, corresponding to a probability ratio of approximately 60:1 in favour of profitability. Conversely, downside risk is limited, with 1.6% of iterations resulting in negative returns. The distribution also shows a 10th percentile (P10) of $1.64 million, indicating that, under adverse conditions (with 90% certainty), potential capital losses are tolerable. The interquartile range (IQR), spanning from $2.55 million (P25) to $5 million (P75), shows that most outcomes are concentrated in the positive domain. In addition, the 90th percentile (P90) of $5.94 million highlights substantial upside potential. The 98.4% probability of success exceeds conventional investment decision thresholds, while the positive expected value and limited downside exposure support the project's feasibility.

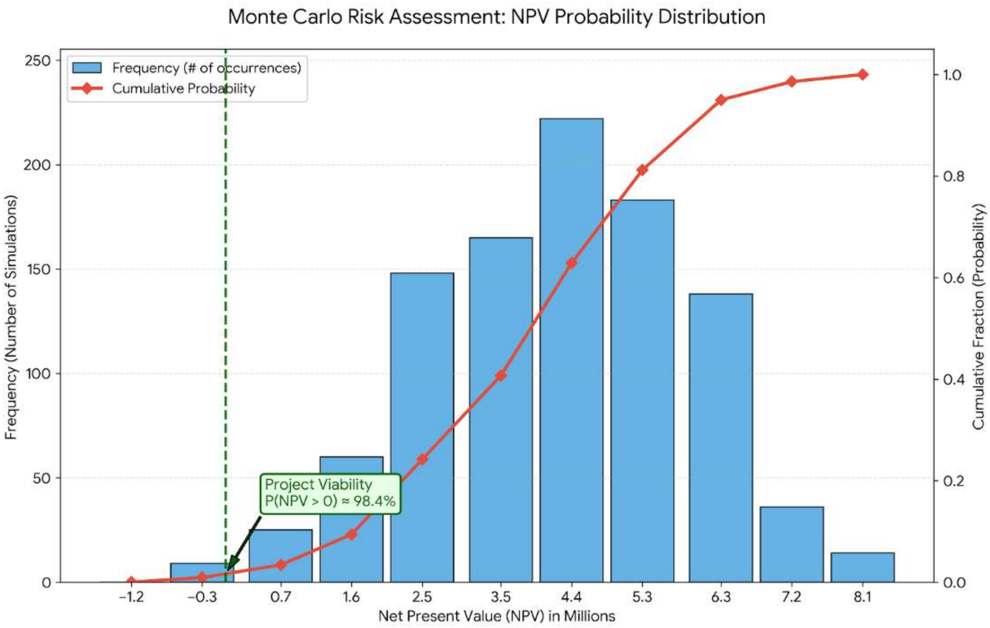

Figure 5: A graph of the probability distribution of NPV

DCFROR Probability Distribution

From Figure 6, the expected mean DCFROR is 16.9%, which is significantly higher than 10% Weighted Average Cost of Capital (WACC). Also, there is 85.0% probability that the project's return will exceed the 10% WACC benchmark, indicating a strong value-creation potential above the cost of capital. The 10th percentile (P10) value of 8.1% sindicates that even in the worst 10% of scenarios, returns remain positive, although they fall marginally below the WACC. Conversely, the 90th percentile (P90) value of 25.1% reveals considerable upside growth potential. The central tendency is well-defined and favourable, with a median DCFROR of 16.9% and a modal range between 16% and 19%, confirming that the bulk of potential outcomes are clustered well above the hurdle rate, thereby establishing the stability of expected returns.

DPBP Probability Distribution

From Figure 7, the median (P50) payback period is 7.0 years, indicating that in many successful scenarios, the initial capital investment is recovered within the first third of the project's 22-year lifespan. According to the frequency analysis, the most common outcome (mode) is that 46% of the scenarios return investment within the 3.2–6.5-year range. Furthermore, 73.9% of all successful scenarios achieve payback within 10 years. Conversely, long payback periods are rare; only 5.0% of successful outcomes require more than 20 years to recover capital. This concentration of outcomes in the fast-to-moderate recovery range indicates project feasibility, as capital exposure to long-term market risks is minimal.

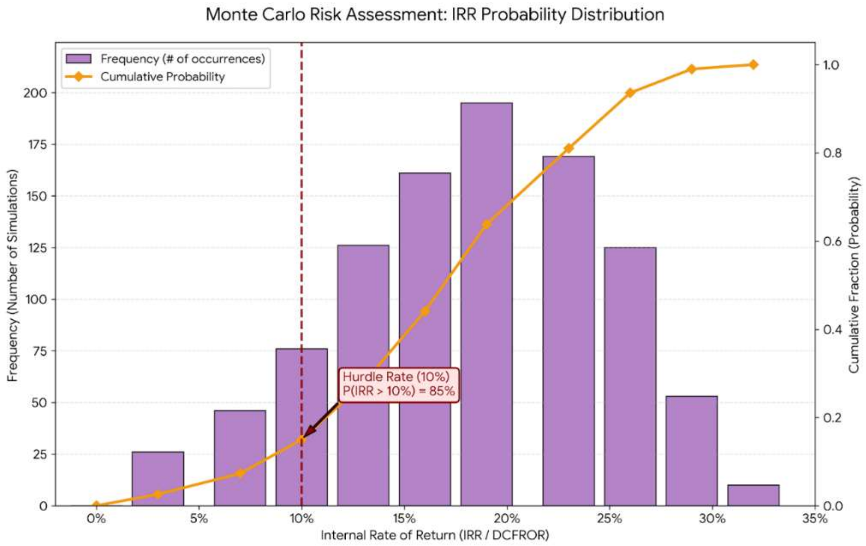

Figure 6: A graph illustrating the DCFROR probability distribution

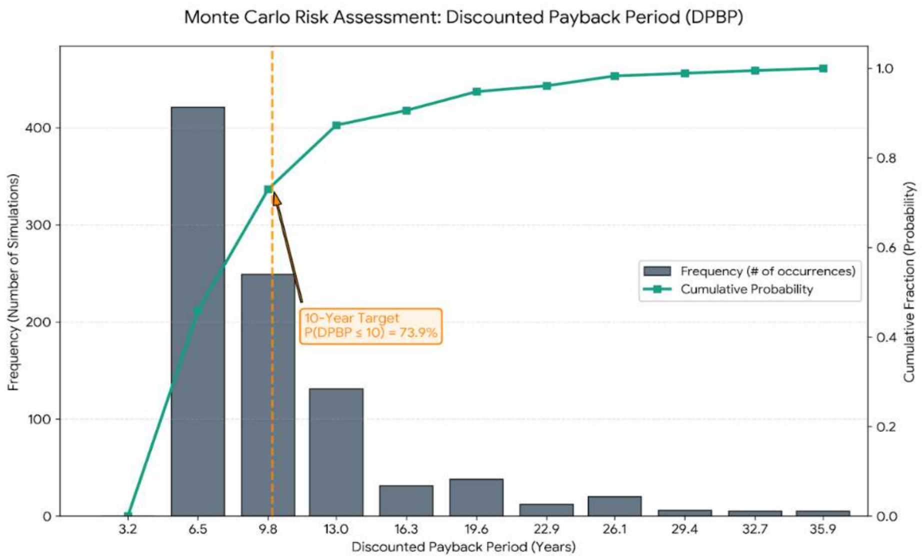

Figure 7: A graph showing the probability distribution of the DPBP

Conclusion

This study successfully demonstrated the techno-economic feasibility, operational stability and financial resilience of converting underutilised rice husk into fuel-grade bioethanol for E10 gasohol production in Nigeria. It bridges the gap between theoretical biomass conversion and commercial-scale deployment by combining steady-state and dynamic process modelling in Aspen HYSYS with detailed capital costing using CAPCOST_2017. Enzymatic hydrolysis, co-fermentation integration, and dilute-acid pretreatment produced favourable overall efficiency. Furthermore, the ethanol-water azeotrope was eliminated using a glycerol-based extractive distillation approach, delivering the required bioethanol purity. The plant's ability to convert underutilised rice husk into bioethanol annually and its comparatively low capital intensity made this pathway a viable source of second-generation biofuel. Moreover, through dynamic simulation of the blending process with ratio controllers, the facility maintained a 10:90 bioethanol-to-gasoline ratio, ensuring that the E10 product satisfies market fuel specifications.

This study, therefore, offers a comprehensive pathway for the commercial-scale utilisation of an abundant and underutilised agricultural residue. The strategy offers a sustainable way to diversify Nigeria's energy mix and economically empower rural areas by avoiding the food-fuel conflict.

ABBREVIATIONS

TEA	Techno-Economic Analysis
FTIR	Fourier-Transform Infrared Spectroscopy
CEPCI	Chemical Engineering Plant Cost Index
MOC	Material of Cost
PEC	Purchased Equipment Cst
BMC	Bare Module Cost
BEC	Base Equipment Cost
BBM	Base Bare Module Cost
DCFROR	Discounted Cash Flow Rate of Return
DPBP	Discounted Payback Period
NPV	Net Present Value

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AUTHOR CONTRIBUTIONS STATEMENT

Prof O. A Falode and Dr O. A. Akinsanoye provided supervision throughout the study, offering guidance on the conceptualisation, methodology, and manuscript preparation.

CONFLICT OF INTEREST STATEMENT

The authors declare there are no competing interests.

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