TECHNO-ECONOMIC ASSESSMENT OF TRANSFORMING SORGHUM BAGASSE INTO BIOETHANOL FUEL IN NIGERIA: 1 - PROCESS MODELLING, SIMULATION, AND COST ESTIMATION

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Abstract: Apart from the environmental threats posed by fossil fuel due to emissions of greenhouse gases (majorly CO_2), Nigeria's economy's continuous reliance on only one source of fuel production is unsustainable, hence, the need to consider diversification and alternative sources of energy generation and fuel production. This work aims to model and simulate the process of transforming sorghum bagasse into a fuel grade bioethanol via the use of Aspen HYSYS and MATLAB for the development and evaluation of cost implications and demand of the concerned plant studied. The study of process plant models shows that 189 g of fuel grade bioethanol will be obtainable from a kilogram of sorghum bagasse based on the condition employed in the modeling of the process. Cost analysis indicates that it would require a capital and operation cost worth of $1.92 and $ 0.83, respectively, to produce a liter of fuel grade bioethanol from sorghum bagasse.

Keywords: sorghum, bagasse, modeling, bioethanol, biofuels, process economics

1. INTRODUCTION

One of the most potent tools in combating vehicular pollution is Bioethanol. It is an alcohol produced from the process of fermenting Sugar, starch or cellulosic biomass. It contains 35% oxygen, which helps in the complete combustion of fuel and turn, enhances the reduction of harmful tailpipe emissions [1].

Bioethanol is experiencing rapid growth in industrialization and also emerging as a global market, which is becoming increasingly crucial by drawing both public and scientific attention basically due to its attractive properties, fluctuating price of oil, and the need for increased energy security. The use of bioethanol is essential to reduce the reliance on non-renewable energy resources like oil and coal [2].

Notable among other reasons to look beyond the oil and gas and delve into an alternate source of energy production is the environmental threats posed by fossil fuels which are associated with the emissions of greenhouse gases (majorly CO_2) which are connected to climate change and other disastrous effects on the earth and its habitants [3,

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4]. According to Galadima et al. [5], about 75% of the Carbon dioxide made by humans was from the burning of fossil fuels. He also reported that Nigeria is contributing the most significant portion of this emission in Sub-Saharan Africa, and particularly, the second world's biggest gas flarer.

For over a century, one of the significant sources of energy in the world is the production of oil and gas. Since the discovery of crude oil in the Delta region in the mid-1950s, it has gradually taken over the heart of Nigeria's economy and gaining ground as the primary source of energy and revenue to the country, side-lining other sectors in the process [6]. Oil and gas currently account for approximately 90% of the country's total government revenues and foreign exchange benefits.

Currently, these commodities accounted for over 90% of both foreign exchange benefits and total government revenues. Total and continuous reliance on this crude oil only spells doom for Nigeria's economy especially, considering the recent global crash in the price of crude oil, which has, in turn, negatively affected the economic strength of the Nigerian people. Also, the current reserves of 36.22 billion barrels and 181 trillion cubic feet of oil and gas could only last for the next 35 to 40 years. This only implies that the days of the consistent flow of oil and gas are numbered, which could be attributed to the rapid increase in population and increased rate of energy consumption, among other factors [7]. Researches have been looking into the feasibility of establishing biofuel refineries in Nigeria. Some of these works are bioethanol production from cassava [8], sugarcane bagasse [9], molasses [10], combine sugarcane-bagasse-juice [11] and others [12]. However, no work has looked into the economics of employing the use of sorghum bagasse for the production of biofuel (bioethanol in particular).

This study seeks to model, simulate and investigate cost implication of establishing or building a process plant set up for the transformation of sorghum bagasse into bioethanol fuel in Nigeria with the aid of Aspen HYSYS and MATLAB application software. This task entailed process flowsheet development, material, and energy analysis, costing of process plant equipment, estimation of total capital investment, and cost of manufacturing/production in Nigeria.

2. MATERIALS AND METHODS

2.1. Study framework

The approach adopted in this research can be illustrated diagrammatically in Figure 1. It begins by sketching the block flow diagram for the proposed process and concludes by presenting the material and energy analysis, cost estimation, and the developed process flow diagram. Total capital investment estimation and cost of manufacturing were also factored into the cost estimation.

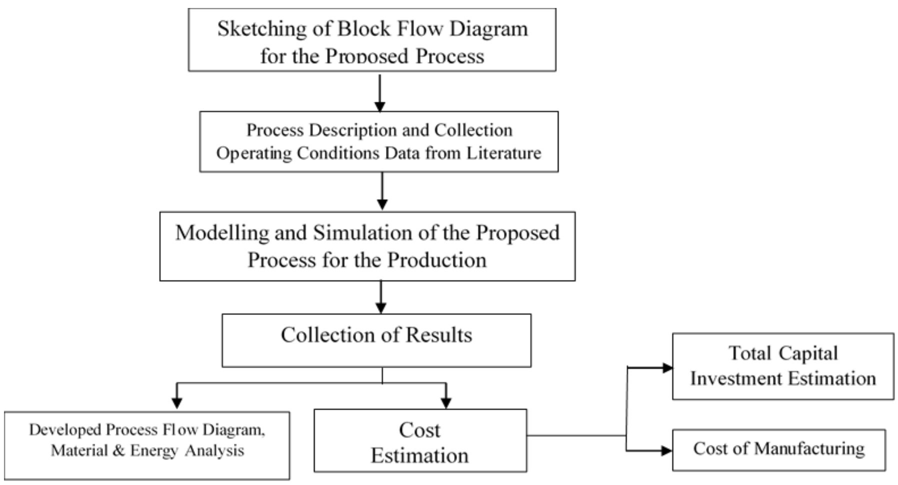

Fig. 1. Research approach framework.

2.2. Process description

Bioethanol production begins with a crushed and pre-treated sweet sorghum stalk feed whose compositions are presented in Table 1. The feed in the modeled plant was extracted to remove juice from sorghum stalk. The resulting product of extraction composing of sucrose, hemicellulose, and cellulose was hydrolyzed in different reactors.

Table 1. Feedstock composition and operating conditions.

Component Name	Value
Cellulose*	0.07
Hemicellulose*	0.04
Lignin*	0.03
Sucrose	0.10
H_2O	0.73
Glucose (as Dextrose)	0.02
Fructose (as Dextrose)	0.02
Vapour / Phase Fraction	0.00
Temperature [ºC]	25.00
Pressure [atm]	2.00
Mass Flow [kg/h]	50,000.00

Adapted from Gnansounou et al. [13], Kim & Day [14], Mamma et al. [15], Sergio et al. [16].

After hydrolysis, the fermentable sugars were fermented. The raw bioethanol produced was then purified. The entire process is diagrammatically summarized in the blocks flow diagram presented in Figure 2, which was employed to modeled and simulated using Aspen HYSYS 8.0 following the procedures presented in Figure 3.

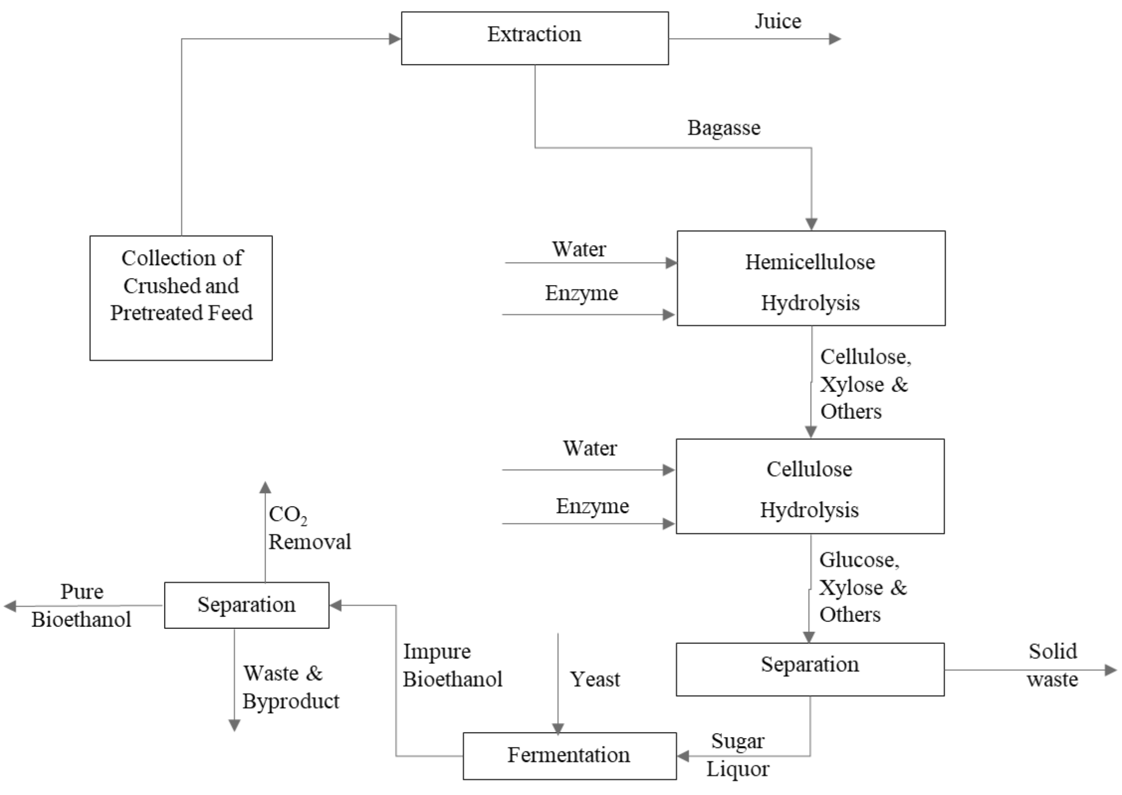

Fig. 2. Block flow diagram for the conversion of sorghum bagasse to bioethanol fuel.

The extracted sorghum juice from hydro-cyclones was sold out for sugar production while the bagasse was used for bioethanol production. In this process, the extracted bagasse was hydrolyzed in the presence of enzymes at the temperature of 50ºC to glucose and xylose. The fermentable sugar stream was then prepared to meet the operating conditions and then passed to the fermentation reactor, where sugar was converted to bioethanol and carbon dioxide in the presence of an enzyme called yeast. The raw products are then purified in a flash, absorber, and distillation columns.

2.3. Process modelling

In this research, a process simulation approach has been adopted using Aspen HYSYS 8.0 process simulator, MATLAB and Microsoft Excel 2013 in modeling and simulating different process flow diagrams for different process technologies for the production of bioethanol from sorghum bagasse. Aspen HYSYS is a robust simulator with a considerable measure of accuracy [17]. In simulating the process technology, the stage-wise procedures illustrated diagrammatically in Figure 3 were employed.

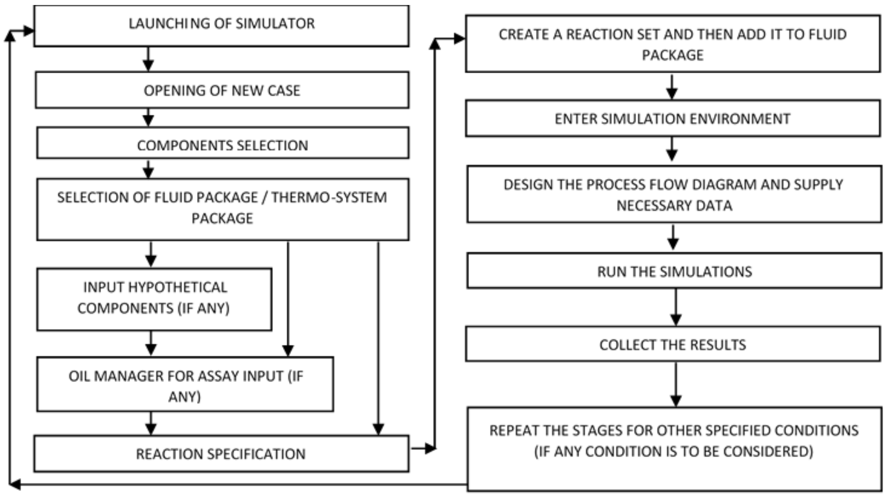

Fig. 3. Flow chart for simulating a process in Aspen HYSYS [11, 18].

2.3.1. Plant simulations assumptions

The following assumptions were made for the plant simulations:
- The feedstock is crushed, washed, and pre-treated with Phosphoric acid and Sodium hydroxide.
- One hundred polymeric units have been assumed for the cellulose model.
- Cooling water is fed at 25 ^{o}C and 1 atm.

Other operating conditions that might not be presented here in this report for any unit operations and processes of interest can be found in the report of Olateju [19].

2.3.2. Simulation components

In modeling the process plants, itemized in Table 2 are the components selected from the Aspen HYSYS components library and those that were hypothetically modeled, which were otherwise known as hypothetical components not induced in the library. They were represented by specifying their typical boiling point, molecular weight, density, diameter, molecular formula from literature while other properties were estimated with the aid of Aspen HYSYS estimator. These are presented in Table 3.

Table 2. Aspen HYSYS pure and hypothetical components involved in this process.

Name	Chemical Formula	Process Application
Carbon dioxide	CO_2	Fermentation product
Ethanol	C_2H_6O	Fermentation product
Glucose (or Dextrose)	$C_6H_{12}O_6$	Hydrolysis product
Water	H_2O	For hydrolysis and washing
Sucrose	$C_{12}H_{22}O_{11}$	Feedstock
Xylose	$C_5H_{10}O_5$	Hydrolysis product
Cellulose	$(C_6H_{10}O_5)_n$	Feedstock
Hemicellulose	$(C_5H_8O_4)_n$	Feedstock
Lignin	$(C_{31}H_{34}O_{11})_n$	Feedstock
Enzyme	$CH_{1.57}N_{0.29}O_{0.31}S_{0.007}$	Enzymatic hydrolysis
Furfural	$C_5H_4O_2$	By-product of hydrolysis
Yeast	Undefined*	Fermentation bacteria
Z. mobilis	$CH_{1.8}O_{0.5}N_{0.2}$	Fermentation bacteria

Note: * was modeled as Z. mobilis since Yeast is a unicellular fungus and not a chemical compound; hence, it has no chemical formula.

Table 3. Hypothetical components and their properties.

Component	Specified Properties
Xylose	Chemical Formula: $C_5H_{10}O_5$ NBP, Ideal Liquid Density, Molecular Weight$^{(E)}$
Cellulose	Chemical Formula: $(C_6H_{10}O_5)_n$ where n = 100 units Density, Molecular Weight$^{(E)}$, Diameter$^{(A)}$
Hemicellulose	Chemical Formula: $(C_5H_8O_4)_n$ where n = 10 units Density$^{(A)}$, Molecular Weight$^{(E)}$, Diameter $^{(A)}$
Lignin	Chemical Formula: $(C_{31}H_{34}O_{11})_n$ where n = 10 units Density$^{(A)}$, Molecular Weight$^{(E)}$, Diameter $^{(A)}$
Enzyme	Modeled as Glucose, Chemical Formula: $CH_{1.57}N_{0.29}O_{0.31}S_{0.007}$ Density, Molecular Weight$^{(E)}$, Diameter$^{(A)}$
Z. mobilis	Modeled as Glucose, Chemical Formula: $CH_{1.8}O_{0.5}N_{0.2}$ Density, Molecular Weight$^{(E)}$, Diameter$^{(A)}$
Cellubiose	Chemical Formula: $(C_6H_{10}O_5)_n$ where n = 200 units Density, Molecular Weight$^{(E)}$, Diameter$^{(A)}$

Note: $^{(E)}$ represent estimated property, $^{(A)}$ represent assumed property

2.3.3. Material and energy analysis for production process

With the aid of Aspen HYSYS 8.0 in-built command, the following process variables were determined from the material and energy balance analysis:

- Energy constraint for both heating and cooling duties for different units;
- Material resource that would be needed for effective and efficient production;
- Equipment Specification for costing basis and bioethanol production quantity.

2.4. Cost estimation

The results of material and energy analysis of the modeled and simulated process technologies were used to determine the size and cost process of equipment, after which the resulting total cost of purchasing equipment for the different respective technologies was determined using the procedure in subsection 2.4.2. Furthermore, both total capital investment and the cost of manufacturing were evaluated using the approach in subsections 2.4.3 and 2.4.4, respectively.

2.4.1. Project parameters and assumptions

In assessing the techno-economic feasibility study of the processes, the following project parameters and assumptions presented in Table 4 were employed in the different profitability analysis.

Table 4. Project parameters and assumptions.

Parameters	Values
Working time	24 hours per day, for 335 days per year
Raw material (1)	Sorghum stalk 50,000 kg per hour for 26 NGN/kg
Discount rate	10.00 %
Working capital rate (2)	5.00 % per year
Proposed product price	0.50-0.67 S/L (100-133 NGN/L)
Currency conversion rate	199 NGN/$ (2016), 365 NGN/$ (2020)
Tax rate	20.00 % per year
The economic life of the project	25.00 years
Depreciation method (3)	Straight Line
Depreciation period	10 years
Profit	6 %

Note: 1Nationa Beaurue of Statistics 2012, 2Richardson and Coulson 20; (2005) [20]

2.4.2. Plant equipment costing

Using Marshall and Swiss cost correlation and indices with equation (1) [21] with the aid of Microsoft Excel 2013, each unit equipment cost were estimated as C_i while the resulting cost was escalated respectively using the equation (2) to evaluate an updated cost of each unit equipment as C_x.

$$C_i = C_o * S^n \tag{1}$$

$$C_x = C_i * (MS_x / MS_n) \quad (2)$$

where C_i are cost as at i year, C_o are bare cost at i year, C_x are escalated cost as at x year, S are size of equipment, n are cost index, MS are marshall and swiss cost index at n and x year.

2.4.3. Total capital investment estimation

The estimation of the capital investment was carried out using the data collected from the sources shown in Table 5.

Table 5. Sources of data for total capital investment estimation.

Items	Source of data
Direct Plant Cost	
Purchased cost of equipment	Sinnott [21], Sieder and Seader [22], Max et al., [23]
Equipment installation cost	Sinnott [21]
Piping installation cost	Sinnott [21]
Electricity installation cost	Sinnott [21]
Instrumentation and control	Sinnott [21]
Building and services	Sinnott [21]
Excavation and site preparation	Sinnott [21]
Auxiliaries/service facilities	Sinnott [21]
Land survey & cost	Sinnott [21]
Indirect Plant Cost	
Field & construction expense	Sinnott [21]
Engineering & supervision	Sinnott [21]
Other Plant Cost	
Contractor's fee, overhead, and profit	Sinnott [21]
Contingency	Sinnott [21]
Working Capital	Sinnott [21]

Using factorial method and purchased equipment cost [21] with the aid MATLAB program code documented in Olateju [19] using equations (3) to (10), total capital investment was estimated as:

Escalated Purchased Equipment Cost, PCE = input (3)

$$\text{Direct Plant Cost, } DPC = 2.93 * PCE \quad (4)$$

$$\text{Indirect Plant Cost, } IPC = 1.76 * DPC \quad (5)$$

$$\text{Total Plant Cost, } TPC = DPC + IPC \quad (6)$$

$$\text{Other Plant Costs, } OPC = 0.15 * TPC \quad (7)$$

$$\text{Fixed Capital Investment, } FCI = TPC + OPC \quad (8)$$

$$\text{Working Capital, } WC = 0.05 * FCI \quad (9)$$

$$\text{Total Capital Investment, } TCI = FCI + WC \quad (10)$$

2.4.4. Cost of manufacturing estimation

The estimation for the cost of manufacturing was done with the use of relevant data sourced from the references presented in Table 6 for each item.

Table 6. Sources of some data for the cost of manufacturing estimation.

Items	Source of data
Raw Material (RM)	NBS Report for 2010-2012; Furla et al., [24].
Utilities Cost (UT), e.g., Cooling water, Electricity, Waste management, etc.	KEDCO Bill Report, Sinnott [21], Seider & Seader [22].
Plant Overhead (PO) Information	Sinnott [21]

Using the factorial method and case-study based cost data for raw material, operating labor and utilities costs were estimated using MATLAB. The manufacturing cost was estimated from the direct production cost, fixed manufacturing cost, and general expenses.

3 RESULTS AND DISCUSSION

3.1 Process flow-sheeting output

The process flow diagram for the bioethanol production from sorghum bagasse is presented in Figure 4, which was built with the use of the block flow diagram presented in Figure 2.

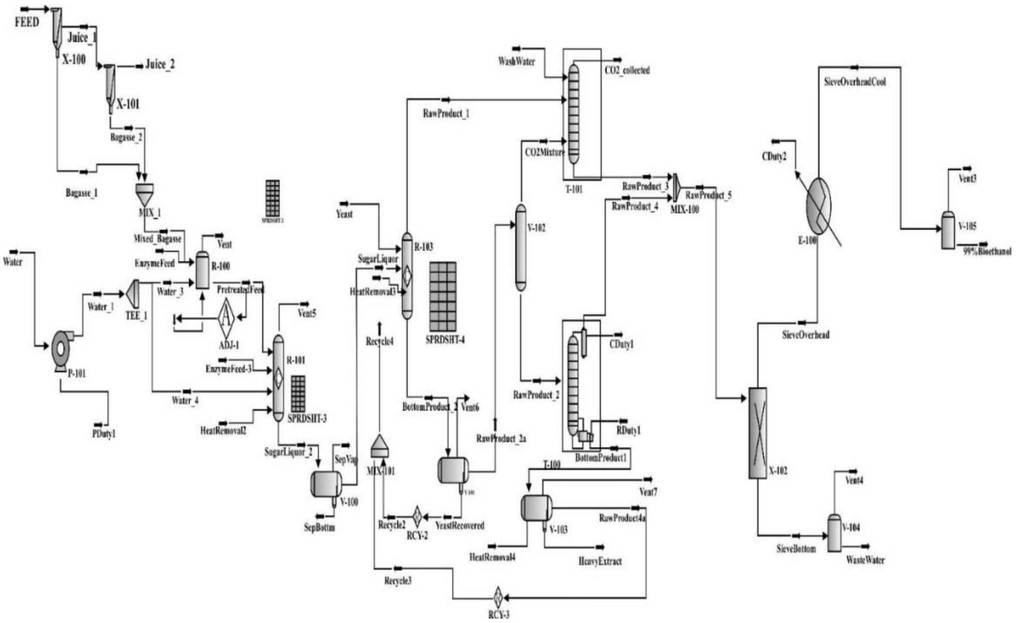

Fig. 4. PFD for bioethanol production from sorghum bagasse.

3.2. Material analysis results

The results of the overall material balance for the flow of materials throughout the process plant simulated are summarized and presented in Table 8. The error of 0.00% obtained from the analysis indicated that there exists a good balance in the rate at which materials flow in (57,817.04 kg/h) and out (57,817.04 kg/h) of the processing units of the plant. And that the law of conservation of mass is maintained through the processes involved in the transformation.

Table 8. Results of the plant overall material balance.

Material Stream Inlet	Flow Rate (kg/h)	Material Stream Outlet	Flow Rate (kg/h)
Yeast	813.46	Vent5	0.00
Enzyme Feed-3	3,553.57	Vent	0.00
Enzyme Feed	3,327.95	Juice_2	579.91
Water	50.00	CO_2_ collected	13,682.24
Feed	50,000.00	Vent6	0.00
Wash Water	72.06	99%Bio-ethanol	9,407.69
		Vent3	0.00
		Waste Water	41.51
		Vent4	0.00
		SepVap	0.00
		Sep Bottm	31,701.37

		Vent7	0.00
		Heavy Extract	0.00
		Recycle4	2,404.32
Material Inlet	57,817.04	Material Outlet	57,817.04
		Error (%)	0.00

Moreover, findings from this study reveal that 9,408 kg of fuel grade bioethanol was produced from the use of 50,000 kg of sorghum bagasse, 6882 kg of enzyme, and 813 kg of yeast in an hour. This implies that 189 g of fuel grade bioethanol will always be obtained from a kilogram of sorghum bagasse, which was found to be lower compared to combine sugarcane-bagasse-juice, which was reported by Oyegoke & Dabai [11] as 292 g/kg (14,618/50,000 kg/kg). However, it was found to be greater than that reported by Abemi et al. [10] as 117 g/kg (8,238/70,000 kg/kg) for the use of molasses.

3.3. Energy analysis results

The results of the overall energy balance for the simulated plant are presented in Table 9, which displayed the flow of energy across the units of process plant modeled. The energy analysis findings indicate that there exists a good balance when total inflow and outflow of energy across the units of the modeled plant compared except for the slight error of 0.06% which was due to the hypothetical component introduced in the modeling of the plant when some component was found missing in the simulator component libraries for compounds [10, 11].

Table 9. Results of plant overall energy balance.

Energy Inlet	Flow Rate (kJ/h) x 10^8	Energy Outlet	Flow Rate (kJ/h) x 10^8
Yeast	0.0000340	Vent5	0.00
Heat Removal3	-0.170	Vent	0.00
Enzyme Feed-3	0.00	Juice_2	-0.0477
Heat Removal2	-1.09	CO2_ collected	-0.917
Enzyme Feed	0.00	Vent6	0.00
Heat Removal1	-0.0520	99%Bio ethanol	-0.568
Water	0.00	Vent3	0.00
PDuty1	0.0000000443	Waste Water	-0.0064
Feed	-0.0899	Vent4	0.00
WashWater	-0.0114	SepVap	0.00
HeatRemoval4	-0.008.93	SepBottm	0.206
RDuty1	7.66	Vent7	0.00
		Heavy Extract	0.00
		CDuty2	0.095
		CDuty1	7.56
		Recycle4	-0.0915
Energy Inlet	6.24	Energy Outlet	6.23
		Error (%)	0.06

The study reveals that the plant energy flow in, which represents the total amount of heat that flows into the plant, is worth 624 million kJ per hour. The value was found to be lower compared to the obtained as 1.08 billion kJ/h and by Oyegoke & Dabai [11] for the use of combined sugarcane-bagasse-juice.

The total purchase cost of equipment was estimated to be 9 million dollars, where the reactor cost proved to contribute an alarming approximately 95.7% of the entire cost. In contrast, the cost of molecular sieve made the least contribution to the total costs. The total purchase cost of equipment was found to be equivalent to the cost reported for the use of combined sugarcane-bagasse-juice in the report of Oyegoke and Dabai [11].

3.4. Plant equipment costing

The results obtained from the costing (in United States Dollars ($)) of the plants' equipment are presented in Table 10.

Table 10. Results of plant equipment costing.

Descriptions	Purchase Cost ($)	Escalated Purchase Cost
Cost of hydro-cyclone	2,788.21	4,129.81
Cost of vessels	181,123.87	248,933.94
Reactor cost	6,233,430.37	8,567,133.65
Column tray & tower cost	25,127.45	34,534.79
Cost of molecular sieve	711.58	1,053.98
Cost of other process facilities	69,773.80	103,363.66
Total cost	6,512,955.28	8,959,149.83

3.5. Total Capital Investment Estimation

The estimation of the total capital investment is presented in Table 11, while Table 12 presents the total capital investment adapted from existing literature.

Table 11: Results for plant total capital investment.

Description	Symbol	Amount ($)
Purchased Cost of Equipment	PCE	8,960,000
Direct Plant Cost	DPC	26,300,000
Indirect Plant Cost	IPC	15,800,000
Total Plant Cost	TPC	42,000,000
Fixed Capital Investment	FCI	48,300,000
Working Capital	WC	2,420,000
Total Capital Investment	TCI	50,700,000
Capital per Liter	CPv	1.92

The result shows reveal that the total capital investment (TCI) is worth 50.7 million dollars and showing that it would cost $1.92 to produce a liter of fuel grade bioethanol from sorghum bagasse.

Table 12. Results for related plants in literature on total capital investment.

Description	Code	Plant Unit	W Amount	H Amount
Total Capital Investment	TCI	M$	22.64	34.08
Capital per Litre	CPv	$/L	0.57	0.43

Adapted from: Idaho Department of Water Resource Energy Division [12].

Note: H=Southwest, and W=Panhandle Plant.

This was found to be more capital intensive when compared to other plants in Idaho presented in Table 12 collected from the report of the Idaho Department of Water Resource Energy Division [12]. The survey of the literature indicated that the use of combine sugarcane-bagasse-juice (0.34 $/L) and molasses (0.10 $/L) less capital demand compared to sorghum bagasse [10, 11].

3.6. Operating Cost Estimation

The estimation of operation cost is presented in Table 13. From the results presented therein, the total operating cost of the plant was estimated to be 118 million dollars. From which, the raw material cost (82.7 million dollars) was found to be mainly contributed to the cost of operation. This raw material cost entails both the sorghum bagasse, enzymes and yeast cost used in the production of bioethanol.

Table 13. Operating cost estimation results.

Description	Symbols	Amount
Raw Material	RM	$82,700,000
Operating Labour	OL	$89,900
Utilities	UT	$2,100,000
Direct Supervision	DS	$10,800

Maintenance & Repair	MR	$1,450,000
Operating Supply	OS	$188,000
Lab charges	LC	$108,000
Patent & Royalties	PR	$2,360,000
Fixed maintenance cost	FMC	$5,950,000
Depreciation	DP	$4,830,000
Plant Overhead cost	PO	$539,000
General experience	GE	$18,200,000
Total operating cost	TOC	$118,000,000
Cost per liter	CP	$0.8253

Furthermore, it was deduced that the operation cost worth of $ 0.83 would be required to produce a liter of fuel grade bioethanol. This cost was found to be more expensive to operate when compared to the plants reported by Idaho Department of Water Resource Energy Division [12], which was summarized in Table 14.

Table 14. Operating cost of related plant in literature.

Description	Code	Plant (Unit)	H (Amount)	W (Amount)
Cost of Manufacturing	COM	M$	18.18	34.38
Cost per Litre	CPv	$/gal($/L)	2.26 (0.60)	1.70 (0.45)

Adopted from: Idaho Department of Water Resource Energy Division [12].

Note: H=Southwest, and W=Panhandle Plant.

Also, the report of Oyegoke et al. [9] indicates that producing bioethanol from sugarcane bagasse (0.50 $/L) is more operation cost less compared to sorghum bagasse (0.83 $/L). Other reports are that of Oyegoke & Dabai [11] and Abemi et al. [10] present 0.61 $/L and 0.60 $/L for the cost of operations for the processing of combine sugarcane-bagasse-juice and molasses only respectively which were found to be less expensive to the use of sorghum bagasse.

4 CONCLUSIONS

This study showed that that 9,408 kg of fuel grade bioethanol was produced from the use of 50,000 kg of sorghum bagasse, 6882 kg of enzyme, and 813 kg of yeast in an hour. Also, it shows that 189 g of fuel grade bioethanol is obtainable from a kilogram of sorghum bagasse based on the condition employed in the modeling of the process.

Cost analysis indicated that the total purchase cost of equipment was found to be 9 million dollars (where the reactor cost proved to contribute an alarming approximately 95.7% of the entire cost). Moreover, this study reveals that the total capital investment of this project is worth 50.7 million dollars, which implies that it would require a capital cost of $1.92 to produce a liter of fuel grade bioethanol from sorghum bagasse. The total operating cost or cost of manufacturing bioethanol was found to be 118 million dollars, which indicated that the operation cost worth of $ 0.83 would be required to produce a liter of fuel grade bioethanol.

The model plant was found to be cost-intensive when compared to other existing reports for bioethanol production plant. This, therefore, suggest the need for further works to look into the optimization of both cost and process to reduce the financial implications or demands.

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