

Energy analysis of unit operations in bioethanol production from cow manure

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Abstract: This research focuses on energy consumption in eight defined unit operations (mixing, sieving, alkaline treatment, drying, milling, hydrolysis, fermentation, distillation) of bioethanol production from cow manure. Data for energy analysis were obtained through direct measurements from a developed bioethanol plant for the production of ethanol from cow manure. The energy analysis was evaluated with 10, 15 and 20 kg of cow manure using ASTM standards. Standard energy equations were used to determine Energy Input, Energy Output, Energy Ratio, Energy Productivity, Net Energy and Net Energy Value (NEV). The computation of energy use was done using Microsoft Excel. One-way analysis of variance was conducted to compare variations and level of significance among the energy inputs and energy indicators in the conversion of cow manure into bioethanol. The results showed that the Energy Input (269.37, 336.12, 402.65 MJ kg⁻¹); Energy Output (94.40, 147.50, 236.00 MJ kg⁻¹); Energy Ratio (0.350, 0.438, 0.586); Energy Productivity (0.0148, 0.0186, 0.0248 MJ/kg); Net Energy (-174.97, -188.62, -166.65 MJ kg⁻¹) and Net Energy Value (0.25, 0.16, 0.10) were obtained for 10, 15 and 20 kg of cow manure, respectively. These values indicated that energy was not efficiently used. Sieving, drying, hydrolysis and distillation were the major energy intensive operations, accounting for over 96% of total energy consumption in the bioethanol production. Thermal energy was mostly used in the bioethanol production stages, representing over 94% of total energy consumption. The one-way analysis of variance showed that there are significant differences in the energy inputs and energy indicators among the unit operations of the bioethanol production. The NEV of less than 1.0 implied that ethanol production from the cow manure was not viable from energy perspectives.

Keywords: ethanol, energy equations, unit operations, manure, bioethanol production.

Citation: Bamgboye, A. I., and O. A. Akinyele. 2026. Energy analysis of unit operations in bioethanol production from cow manure. *Agricultural Engineering International: CIGR Journal*, 28(2):173-186.

1 Introduction

Bioethanol, derived from biomass through biological processes, is a highly promising alternative to petrol in the transportation industry (Woldesenbet et al., 2013). The process of fermenting sugar-containing crops e.g. corn, wheat, sugarcane, sugar beet, potato, sorghum and cassava, yields a substantial quantity of bioethanol. Several alternative options to fossil fuels exist, such as methanol, methane, etc. Akpan et al.

(2024) reported, however, that key properties of ethanol make it ideal as an alternative fuel for automobiles, including high octane and quality ratings, high latent heat of vapourisation, and low toxic mixtures during combustion. Woldesenbet et al. (2013) reported that around 80% of global ethanol production is obtained by fermentation, while the remaining 20% is synthesized from petroleum-based sources like ethylene. Global warming and climate change are caused by the ethanol used as fuel and greenhouse gas.

Received date: 2025-04-01 Accepted date: 2025-09-14

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According to Hoang and Nghiem (2021), global ethanol production has increased more than six-fold from 18 billion litres at the turn of the century to 110 billion litres in 2019, only to fall to 98.6 billion litres in 2020 due to pandemic. Sugarcane and corn have been used as the major feedstocks for ethanol production. Lignocellulosic biomass has recently been considered as another potential feedstock due to its non-food competing status and its availability in very large quantities (Hoang and Nghiem, 2021).

According to Woldesenbet et al. (2013), meeting energy need, associated with transportation, lighting, heating and industrial processes, is the utmost societal challenge these days, which has significantly impacted the environment. Akpan et al. (2024) reported that there is an urgent need to conduct research to discover possible alternative fuels to meet these challenges. The Energy Independence and Security Act (EISA) mandates expanded use of cellulosic biofuel to 16 billion gallons (equivalent to 61 billion litres) in 2022, on a trajectory to surplus corn ethanol use. A wide range of feedstocks that are suitable for conversion would be required for the production of fuel to reach the aspiring goal (Budsberg et al., 2012).

There are a number of factors that have led the society to search for alternative fuels, including the increasing consumption of fossil fuels, adverse impact of fossil fuels on environment, global warming, gradual upsurge in energy demand, inevitable depletion of global energy supplies, and unbalanced oil market (Sebayang et al., 2016). Alternative fuels are projected to meet quite a lot of requirements, as well as considerable reductions in greenhouse gas emissions, obtainability of raw materials worldwide, and ability to use sustainable feedstocks (Nanda et al., 2018). Bioenergy, being a type of renewable energy, is a potential substitute to petroleum-originated fuels and meeting the rising energy need for industrial developments, transportation, heating, and cooling (Prasad et al., 2019). Biogas, biodiesel, and bioethanol are all examples of bioenergy.

Livestock manure is an easily accessible waste

biomass that contains many nutritional elements including nitrogen, phosphorus, and potassium, which can be directly absorbed by certain crops. Furthermore, the integration of organic substance derived from manure into the soil can significantly reduce the likelihood of soil erosion and augment the soil's water retention capacity. Therefore, livestock waste is commonly utilised directly as a soil amendment, but the potential for harnessing energy from the manure is frequently overlooked (Champagne, 2008). Nevertheless, the discharge of microorganisms and nutrients into surface and groundwater, as well as the existence of excessive nitrogen and phosphorus in the soil, unpleasant odours, and the release of greenhouse gases e.g. methane and nitrous oxide, all add to the reduction in economic, health and environmental benefits of utilising manure for this objective (Klein et al., 2010; Miller et al., 2011).

Utilising livestock dung, which includes agricultural wastes, for energy production is increasingly becoming a desirable alternative method of waste management. Currently, the primary method of generating energy from livestock waste is through the creation of biogas (Akinyele, 2024). Animal manure as sources of energy not only got the attention of dairy farms, but the idea has also interested car company. Using bioethanol from animal manure is a cleaner alternative to gasoline-powered cars and natural gas for heating homes. While unconventional, this method of energy production has a lot of potentials. Energy is an essential part of human activities, which is certainly the live wire of industrial and agricultural production, as no action will occur within a system without adopting energy (Akinyele, 2024).

There have been several studies on energy analysis in the production of different feedstocks, but literature is currently sparse on energy analysis in the production of ethanol from livestock manure. Existing studies on energy analysis includes: Energy Input in the Production of Ethanol from Cassava (Bamgboye and Kosemani, 2018), Energy Input in the Production of Cassava (Bamgboye and Kosemani, 2015), Energy

Analysis of a Wheat Processing Plant in Nigeria (Olaoye et al., 2014), Energy analysis for production of local alcohol (Burukutu) in Benue State, Nigeria (Sunday et al., 2013), Analysis of energy usage in the production of three selected cassava-based foods in Nigeria (Jekayinfa and Olajide, 2007), Energetic Analysis of Poultry Processing Operations (Jekayinfa, 2007), Estimating energy requirement in cashew (*Anacardium occidentale L.*) nut processing operations (Jekayinfa and Bamgboye, 2006), etc.

This research therefore focuses on analysing the energy consumption in all the unit operations of bioethanol production from cow manure.

2 Materials and methods

2.1 Experimental procedure

A bioethanol plant consisting of eight-unit operations, namely, mixing, sieving, alkaline treatment, drying, milling, hydrolysis, fermentation, and distillation, was developed using ASTM standards (Akinyele, 2024). Ethanol was produced from the cow manure through biochemical conversion process, while the energy analysis of the bioethanol production was conducted using 10, 15 and 20 kg of cow manure as feedstocks. The eight-unit operations are described as follows:

2.1.1 Mixing

Before the mixing process, the solid manure samples have been separated from debris, stones, bedding materials and any other extraneous particles that could disturb the flow of operation. The three manure samples (cow, pig, and poultry) of 10, 15, and 20 kg each were mixed thoroughly with 15, 20, and 25 litres of water, respectively, to form slurry, and a homogeneous mixture was achieved. After the homogeneous mixture was achieved, the tap was opened to allow the mixed manure to pass out and be discharged into the sieving unit. During the mixing stage, manual and electrical energies were employed, while two persons were involved in the operation. The mixing operation was effective in achieving homogeneous and thorough mixture of the feedstocks.

2.1.2 Sieving

The mixed manure samples were then sieved for solid/liquid separation. As the sieving chamber automatically moves front and back to sieve and separate the content (already in slurry manure), the solid fractions are retained on the sieve, while the liquid content moves down and discharged through the outlet into a container and was disposed-off properly. Manual and thermal energies were employed at this stage, while two persons were involved in the operation. The sieving operation was effective in achieving thorough separation of solid and liquid particles for efficient process.

2.1.3 Alkaline treatment

The solid fractions (sieved manure samples) were treated with 50, 100, and 150 g of Potassium Hydroxide (KOH), respectively. The process enhanced the breaking up of integrated structure of the cellulosic material, even though there was still insufficient access due to the damaged structure for the acid to affect the cellulose molecules. Manual energy only was used at this stage, while the operation involved just one person. The alkaline treatment was effective to improve the acid hydrolysis to glucose.

2.1.4 Drying

The KOH treated manures were subjected to drying using a charcoal-fired dryer to reduce the bulkiness of the feedstock and to degrade the organic matter at a high temperature of 93.5°C, therefore opening up more cellulose. The energies employed at the drying stage include manual, electrical and thermal, while two people were involved in this operation.

2.1.5 Milling

The dried manures were ground (milled) to reduce the particle size of the feedstock and as well creating a larger surface area for reaction. The dried feedstock was milled into a powdery form using a burr mill. Manual and electrical energies were employed at this stage, while the operation involved two persons. The milling operation aided the substrate to become significantly more susceptible to acid interaction.

2.1.6 Hydrolysis

The milled manure samples were hydrolysed with

250, 350 and 450 ml of dilute sulphuric acid (H_2SO_4), respectively, in the tank to aid the process, while the solutions were heated for 30 minutes each. After hydrolysis, the solution was allowed to cool and then filtered into a container using a filtering medium. The liquid fraction (filtrate) was kept for further process while the solid fraction was disposed of. At this stage, just one person was involved in the operation, while manual and thermal energies were employed. The hydrolysis process decomposes the cellulose component of the manure into simple sugar (glucose).

2.1.7 Fermentation

The hydrolysed (sugar) solution was subjected to fermentation, while 100, 150 and 200 g of the yeast (*Saccharomyces Cerevisiae*), respectively, were thawed in 100 ml of warm water each to enhance yeast growth. The yeast was afterward added to three fermented solutions and incubated for 24 hours in a fermentation tank (to be kept warm) for effective fermentation. Manual energy only was used at this stage, while only one person was involved in the operation. The fermentation process aided the production of bioethanol by breaking down of sugar in the absence of oxygen.

2.1.8 Distillation

The fermented sugar solution was finally distilled in a distillation tank to produce bioethanol, heated with gas burner to form steamed solution and cooled through the cooling pipe and inside a cooling box (condenser) before being discharged. The distilled solution (bioethanol) was collected through the discharge outlet on the cooling box into a container. The solution was distilled at a cooling temperature of $70^\circ C - 75^\circ C$. The energies employed at the distillation stage include manual, electrical and thermal, while two people were involved in the operation. The distillation process facilitated the separation of liquids from non-volatile solids with the aid of heat to produce bioethanol.

2.2 Estimation of energy inputs

The energy consumed in converting the cow manure into bioethanol was estimated at each of the

unit operations. Data on energy input sources (human labour, electricity, gas, fuel petrol) were obtained through direct measurements for each unit operation during the bioethanol production. The quantity of inputs utilised in the bioethanol production was calculated based on the unit operations. Standard equations were employed to calculate the energy consumed at each stage of operation and to convert raw data into energy equivalent.

The process flow chart for the conversion of cow manure into bioethanol showing the eight-unit operations (mixing, sieving, alkaline treatment, drying, milling, hydrolysis, fermentation, and distillation) is represented by Figure 1. Energy input from human labour (manual energy), electricity (electrical energy) and fuel such as charcoal, petrol and gas (thermal energy) were all calculated according to Bamgboye and Jekayinfa (2006), Jekayinfa and Bamgboye (2004, 2006, 2007), Jekayinfa and Olajide (2007), Abubakar and Umar (2006).

For uniformity, the energy components (manual, electrical and thermal) for the unit operations and the energy indicators (energy output, energy ratio, energy productivity, net energy and net energy value) were evaluated for the conversion of 10, 15 and 20 kg each of the manure samples, using standard procedure as follows:

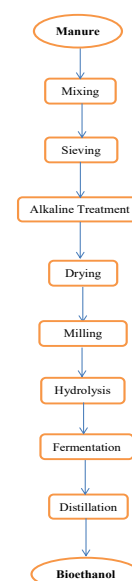


Figure 1 Process flow for conversion of cow manure into bioethanol

2.2.1 Estimation of manual energy

The manual energy was computed using the formula provided by Odigboh (1998), which specifies that the output power of a regular human labourer in tropical conditions is around 0.075 kW held constantly over 8 - 10 hours workday, assuming a maximum constant 0.3 kW energy consumption rate and 25% conversion efficiency. The manual energy for a certain operation was determined by recording the duration of time spent by the worker on each activity, encompassing the entire process from mixing to distillation. This encompassed the sporadic intervals of repose. The manual energy consumed, denoted as E_m ,

was determined for all unit operation using Equation 1 (Bamgboye and Jekayinfa, 2006):

$$E_m = 0.075NT_a \text{ (kWh) or } 3.6[0.075NT_a] \text{ (MJ)} \quad (1)$$

Where,

E_m = Manual energy, in kWh or MJ;

0.075 = Average power output of an average human labourer in tropical regions, measured in kilowatts (kW), or the energy input typical of an adult male;

N = No. of persons engaged in a given task;

T_a = Time expended to complete a specific task in hour;

3.6 = Unit of conversion from kWh to MJ.

Table 1 Quantified parameters for evaluating energy input in the conversion of cow manure into bioethanol

| S/N | Operation | Required parameters |
|-----|--------------------|--|
| 1. | Mixing | Electrical power, kW Time expended on mixing, hr No. of people engaged in mixing Quantity of fuel used, litres |
| 2. | Sieving | Calorific value of fuel used, MJ kg ⁻¹ Time expended on sieving, hr No. of people engaged in sieving |
| 3. | Alkaline Treatment | Time expended on alkaline treatment, hr No. of people engaged in alkaline treatment |
| 4. | Drying | Electrical power, kW Quantity of fuel used, litres Calorific value of fuel used, MJ kg ⁻¹ Time expended on drying, hr No. of people engaged in drying |
| 5. | Milling | Electrical power, kW Time expended on milling, hr No. of people engaged in milling Quantity of fuel used, litres |
| 6. | Hydrolysis | Calorific value of fuel used, MJ kg ⁻¹ Time expended on hydrolysis, hr No. of people engaged in hydrolysis |
| 7. | Fermentation | Time expended on fermentation, hr No. of people engaged in fermentation |
| 8. | Distillation | Electrical power, kW Quantity of fuel used, litres Calorific value of fuel used, MJ kg ⁻¹ Time expended on distillation, hr No. of people engaged in distillation |

2.2.2 Estimation of electrical energy

The electrical energy was computed by multiplying the rated horsepower of the electric motor/compressor and the duration of operation in hours. According to Rajput (2001), an efficiency of 80% was assumed for electric motor/compressor to compute the electric inputs. The electrical energy was thus calculated for all unit operations using Equation 2 (Jekayinfa and Bamgboye, 2004, 2006, 2007):

$$E_p = \eta Pt \text{ (kWh) or } 3.6[\eta Pt] \text{ (MJ)} \quad (2)$$

Where,

E_e = Electrical energy consumed, in kWh or MJ;

η = Power factor (assumed to be 0.8);

P Rated horsepower of the electric motor/compressor, kW;

t = Duration of operation in hours, hr;

3.6 = Unit of conversion from kWh to MJ.

2.2.3 Estimation of thermal energy

The thermal energy (energy from fuel) was assigned to some unit operations according to their level of consumption. According to Rajput (2001), the total quantity of energy consumed from fuel was converted to common energy unit (Joule) by multiplying the quantity of fuel consumed by the corresponding calorific value (lower heating value) of the fuel used. The thermal energy was calculated for all unit operations using Equation 3 (Jekayinfa and Olajide, 2007):

$$E_t = C_f W \quad (3)$$

Where,

E_t = Thermal energy consumed, MJ;

C_f = Calorific (heating) value of fuel, MJ kg⁻¹ (charcoal = 28; petrol = 42.3; gas = 46);

W = Quantity of fuel (charcoal, petrol, and gas) used, kg.

Quantitative data on operational conditions were measured to access the energy components (manual, electrical and thermal) in all the eight-unit operations of the bioethanol plant. Based on the conversion stages as outlined in Figure 1, the measured parameters to evaluate the energy use at the unit operations are given in Table 1.

2.3 Energy equations for the unit operations

The energy consumed in converting the cow manure to bioethanol was calculated, considering the human labour conditions for handling, operating the machine, and any other related tasks. Thus, Equations 4-11 give typical energy equations formed for the unit operations from mixing to distillation stage.

2.3.1 Mixing

The energy required (E_{mx}) for mixing raw manure with water was obtained from Equations 4a and 4b:

$$E_{mx} = 3.6[0.075N_{mx}T_{mx} + \eta_{mx}P_{mx}t_{mx}], \text{ when electricity is used} \quad (4a)$$

$$E_{mx} = 3.6[0.075N_{mx}T_{mx}], \text{ when mixing is totally carried out manually} \quad (4b)$$

2.3.2 Sieving

The energy required (E_{sv}) for sieving mixed manure

was obtained from Equations 5a and 5b:

$$E_{sv} = 3.6[0.075N_{sv}T_{sv}] + C_{sv}W_{sv} \text{ when fuel (petrol) is used} \quad (5a)$$

$$E_{sv} = 3.6[0.075N_{sv}T_{sv}], \text{ when sieving is totally carried out manually} \quad (5b)$$

2.3.3 Alkaline treatment

The energy required (E_{at}) for treating the sieved manure with potassium hydroxide (KOH) was obtained from Equation 6:

$$E_{at} = 3.6[0.075N_{at}T_{at}], \text{ when alkaline treatment is totally carried out manually} \quad (6)$$

2.3.4 Drying

The energy required (E_{dr}) for drying the KOH treated manure was obtained from Equations 7a, 7b, 7c and 7d:

$$E_{dr} = 3.6[0.075N_{dr}T_{dr} + \eta_{dr}P_{dr}t_{dr}], \text{ when electricity is used} \quad (7a)$$

$$E_{dr} = 3.6[0.075N_{dr}T_{dr}] + C_{dr}W_{dr}, \text{ when charcoal is used} \quad (7b)$$

$$E_{dr} = 3.6[0.075N_{dr}T_{dr} + \eta_{dr}P_{dr}t_{dr}] + C_{dr}W_{dr}, \text{ when electricity and charcoal are used} \quad (7c)$$

$$E_{dr} = 3.6[0.075N_{dr}T_{dr}], \text{ when drying is totally done manually} \quad (7d)$$

2.3.5 Milling

The energy required (E_{ml}) for milling the dried manure was obtained from Equations 8a and 8b:

$$E_{ml} = 3.6[0.075N_{ml}T_{ml} + \eta_{ml}P_{ml}t_{ml}], \text{ when electricity is used} \quad (8a)$$

$$E_{ml} = 3.6[0.075N_{ml}T_{ml}], \text{ when milling is totally carried out manually} \quad (8b)$$

2.3.6 Hydrolysis

The energy required (E_{hd}) for hydrolysing the milled manure was obtained from Equations 9a and 9b:

$$E_{hd} = 3.6[0.075N_{hd}T_{hd}] + C_{hd}W_{hd}, \text{ when gas is used} \quad (9a)$$

$$E_{hd} = 3.6[0.075N_{hd}T_{hd}], \text{ when hydrolysis is totally carried out manually} \quad (9b)$$

2.3.7 Fermentation

The energy required (E_{fm}) for fermenting the hydrolysed solution was obtained from Equation 10:

$$E_{fm} = 3.6[0.075N_{fm}T_{fm}], \text{ when fermentation is totally carried out manually} \quad (10)$$

2.3.8 Distillation

The energy required (E_{dt}) for distilling the fermented solution into bioethanol was obtained from Equations 11a, 11b, 11c and 11d:

$$E_{dt} = 3.6[0.075N_{dt}T_{dt} + \eta_{dt}P_{dt}t_{dt}], \text{ when electricity is used} \quad (11a)$$

$$E_{dt} = 3.6[0.075N_{dt}T_{dt}] + C_{dt}W_{dt}, \text{ when gas is used} \quad (11b)$$

$$E_{dt} = 3.6[0.075N_{dt}T_{dt} + \eta_{dt}P_{dt}t_{dt}] + C_{dt}W_{dt}, \text{ when electricity and gas are used} \quad (11c)$$

$$E_{dt} = 3.6[0.075N_{dt}T_{dt}], \text{ when distillation is totally done manually} \quad (11d)$$

The total energy input in converting the cow manure into bioethanol is the total sum of the energy components engaged in the unit operations. Therefore, the total energy input (E_T) can be expressed as:

$$E_T = E_{mx} + E_{sv} + E_{at} + E_{dr} + E_{ml} + E_{hd} + E_{fm} + E_{dt} \quad (12)$$

Equation 12 enables the computation of the aggregate energy utilised within a defined production rate. The energy analysis for the bioethanol plant under consideration was calculated using Microsoft Excel. This eliminates the necessity of using expensive simulation software and manual computations. Moreover, the computational methodology is readily comprehensible to engineers and operators seeking to assess energy consumption in individual unit

operations at any given moment. The equations will provide the necessary reference information for successful budgeting, accurate energy requirement prediction, and accurate development projection in the conversion of livestock manure into useful products.

2.4 Estimation of energy indicators

The energy indicators, namely energy output, energy ratio, energy productivity, net energy and net energy value, were computed based on the energy inputs derived from the aforementioned equations, following the methodologies outlined by Bamgboye and Kosemani (2015), Bamgboye and Kosemani (2018), Mohammadshirazi et al. (2014), and Taki et al. (2012). The estimation of the energy indicators (Equations 13-17) was based on the energy equivalents of inputs and output, as presented in Table 2.

$$\text{Energy Output (MJ/kg)} = \text{Yield} \times \text{Energy Equivalent of Yield} \quad (13)$$

$$\text{Energy Ratio} = \frac{\text{Energy Output}}{\text{Energy Input}} \quad (14)$$

$$\text{Energy Productivity (MJ/kg)} = \frac{\text{Yield}}{\text{Energy Input}} \quad (15)$$

$$\text{Net Energy (MJ/kg)} = \text{Energy Output} - \text{Energy Input} \quad (16)$$

$$\text{Net Energy Value} = \frac{\text{Energy Equivalent of Yield}}{\text{Energy Output}} \quad (17)$$

Table 2 Energy equivalents of inputs and output in the conversion of cow manure into bioethanol

| Parameters | Energy equivalent | References |
|------------------------------|-------------------|------------------------------|
| Human Labour (h) | 1.96 | Bamgboye and Kosemani (2015) |
| Electricity (kWh) | 11.93 | Taki et al. (2012) |
| Charcoal (kg) | 28 | Rajput (2001) |
| Liquefied Petroleum Gas (kg) | 46 | Rajput (2001) |
| Petrol (litres) | 42.3 | Abubakar and Umar (2006) |
| Manure (MJ) | 0.30 | Mohammadi et al. (2008) |
| Ethanol (MJ) | 23.6 | Walker (2011) |

2.5 Data analysis

One-way analysis of variance (1-way ANOVA) was conducted to compare variations and level of significance among the energy inputs and energy indicators in the conversion of cow manure into bioethanol, using SPSS 25 software package.

3 Results and discussion

3.1 Energy inputs in converting cow manure into bioethanol

The results of the energy inputs in the production of bioethanol from 10, 15 and 20 kg of cow manure were shown in Table 3. The total energy input in converting 10, 15 and 20 kg of cow manure into bioethanol was 269.37, 336.12 and 402.65 MJ kg⁻¹,

respectively. The patterns of energy consumption in the production of bioethanol from 10, 15 and 20 kg of cow manure are presented in Figures 2, 3 and 4, respectively. Thermal energy was mostly used in all the production stages, followed by manual energy and electrical energy. This shows that bioethanol production depends largely on fuel (petrol, gas and charcoal) for operations. It was observed that 94.28%, 94.45% and 94.61% of the total energy input in converting 10, 15 and 20 kg of cow manure into bioethanol was obtained from thermal source, followed by 3.30%, 2.95% and 2.70% obtained from manual energy source, while 2.42%, 2.60% and 2.69% were attributed to electrical energy sources, respectively. This evidently shows that most of the tedious and energy consuming operations involved in the production of ethanol are actually carried out with 96.20%, 96.71% and 97.04%, respectively, of energy consumption attributed to the use of gas, charcoal and internal combustion engine (petrol engine) for operating the machines. The findings in this study were similar to the results obtained by Bamgboye and Kosemani (2018) as well as Bamgboye and Jekayinfa (2006), with the thermal energy being the most consumed energy source.

Considering the unit operations in the bioethanol production from 10, 15 and 20 kg of cow manure, all the operations required manual energy in different measures. The energy use for distillation (93.72,

117.58 and 141.44 MJ kg⁻¹) was the highest, accounting for 34.79%, 34.98% and 35.13% of the total energy consumption in the bioethanol production, respectively. This was followed by drying (59.22, 74.72 and 90.02 MJ kg⁻¹, 21.99%, 22.23% and 22.36%); hydrolysis (55.34, 69.14 and 82.94 MJ kg⁻¹, 20.54, 20.57% and 20.59%) and sieving (50.88, 63.61 and 76.34 MJ kg⁻¹, 18.88%, 18.93% and 18.96%), respectively. Other results include fermentation (6.48, 6.48 and 6.48 MJ kg⁻¹, 2.41%, 1.93% and 1.61%); milling (2.82, 3.38 and 3.95 MJ kg⁻¹, 1.05%, 1.01% and 0.98%); mixing (0.86, 1.16 and 1.45 MJ kg⁻¹, 0.32%, 0.34% and 0.36%) and alkaline treatment (0.04, 0.04 and 0.04 MJ kg⁻¹, 0.02%, 0.01% and 0.01%). It was observed that sieving, drying, hydrolysis and distillation were the major energy intensive operations, accounting for 96.20%, 96.71% and 97.04% of total energy consumption, respectively in the bioethanol production from 10, 15 and 20 kg cow manure. Drying and distillation operations utilised all the available energy sources in the bioethanol production.

The analysis of variance (ANOVA) in Table 4 showed that there are significant variations in the manual energy ($F = 277.622$, $df = 23$, $P < 0.05$), electrical energy ($F = 14.301$, $df = 11$, $P < 0.05$) and thermal energy ($F = 6.385$, $df = 11$, $P < 0.05$) among the unit operations (mixing, sieving, alkaline treatment, drying, milling, hydrolysis, fermentation, distillation).

Table 3 Energy inputs in converting 10, 15 and 20 kg of cow manure into bioethanol

| Unit Operation | Operation Time (hr) | Manual Energy (MJ) | Electrical Energy (MJ) | Thermal Energy (MJ) | Total | % Total |
|----------------------------|---------------------|--------------------|------------------------|---------------------|-------|---------|
| Mixing (10 kg) | 0.18 | 0.09 | 0.77 | - | 0.86 | 0.32 |
| Mixing (15 kg) | 0.24 | 0.13 | 1.03 | - | 1.16 | 0.34 |
| Mixing (20 kg) | 0.3 | 0.16 | 1.29 | - | 1.45 | 0.36 |
| Sieving (10 kg) | 0.23 | 0.12 | - | 50.76 | 50.88 | 18.88 |
| Sieving (15 kg) | 0.3 | 0.16 | - | 63.45 | 63.61 | 18.93 |
| Sieving (20 kg) | 0.37 | 0.20 | - | 76.14 | 76.34 | 18.96 |
| Alkaline Treatment (10 kg) | 0.15 | 0.04 | - | - | 0.04 | 0.02 |
| Alkaline Treatment (15 kg) | 0.15 | 0.04 | - | - | 0.04 | 0.01 |
| Alkaline Treatment (20 kg) | 0.15 | 0.04 | - | - | 0.04 | 0.01 |
| Drying (10 kg) | 1.5 | 0.81 | 2.41 | 56.0 | 59.22 | 21.99 |
| Drying (15 kg) | 2.2 | 1.18 | 3.54 | 70.0 | 74.72 | 22.23 |
| Drying (20 kg) | 2.8 | 1.51 | 4.51 | 84.0 | 90.02 | 22.36 |
| Milling (10 kg) | 0.25 | 0.14 | 2.68 | - | 2.82 | 1.05 |

| Unit Operation | Operation Time (hr) | Manual Energy (MJ) | Electrical Energy (MJ) | Thermal Energy (MJ) | Total | % Total |
|----------------------|---------------------|--------------------|------------------------|---------------------|--------|---------|
| Milling (15 kg) | 0.3 | 0.16 | 3.22 | - | 3.38 | 1.01 |
| Milling (20 kg) | 0.35 | 0.19 | 3.76 | - | 3.95 | 0.98 |
| Hydrolysis (10 kg) | 0.5 | 0.14 | - | 55.2 | 55.34 | 20.54 |
| Hydrolysis (15 kg) | 0.5 | 0.14 | - | 69.0 | 69.14 | 20.57 |
| Hydrolysis (20 kg) | 0.5 | 0.14 | - | 82.8 | 82.94 | 20.59 |
| Fermentation (10 kg) | 24.0 | 6.48 | - | - | 6.48 | 2.41 |
| Fermentation (15 kg) | 24.0 | 6.48 | - | - | 6.48 | 1.93 |
| Fermentation (20 kg) | 24.0 | 6.48 | - | - | 6.48 | 1.61 |
| Distillation (10 kg) | 2.0 | 1.08 | 0.64 | 92.0 | 93.72 | 34.79 |
| Distillation (15 kg) | 3.0 | 1.62 | 0.96 | 115.0 | 117.58 | 34.98 |
| Distillation (20 kg) | 4.0 | 2.16 | 1.28 | 138.0 | 141.44 | 35.13 |
| Total (10 kg) | 28.81 | 8.90 | 6.51 | 253.96 | 269.37 | 100 |
| Total (15 kg) | 30.69 | 9.92 | 8.75 | 317.45 | 336.12 | 100 |
| Total (20 kg) | 32.47 | 10.88 | 10.83 | 380.94 | 402.65 | 100 |
| % Total (10 kg) | | 3.30 | 2.42 | 94.28 | 100 | |
| % Total (15 kg) | | 2.95 | 2.60 | 94.45 | 100 | |
| % Total (20 kg) | | 2.70 | 2.69 | 94.61 | 100 | |

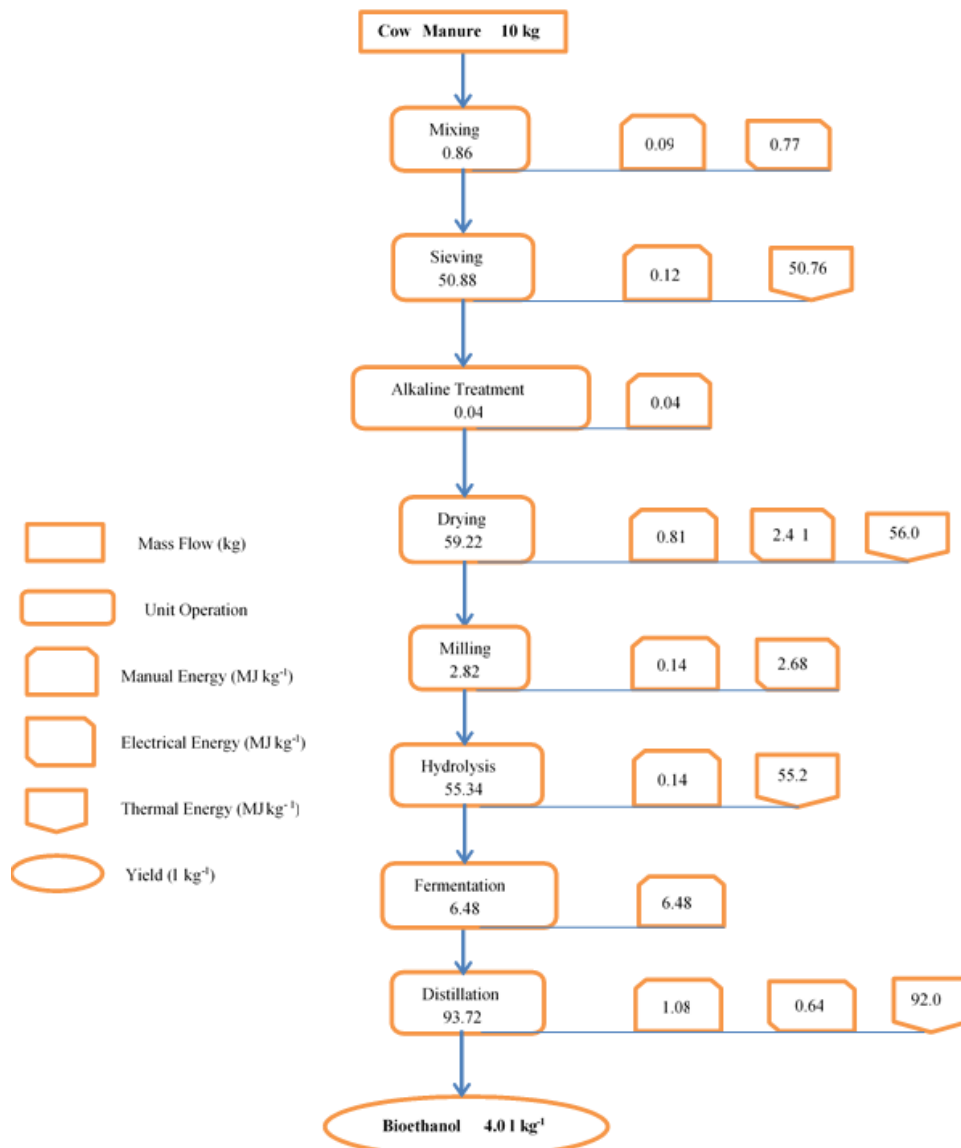


Figure 2 Energy flow diagram for converting 10 kg of cow manure into bioethanol

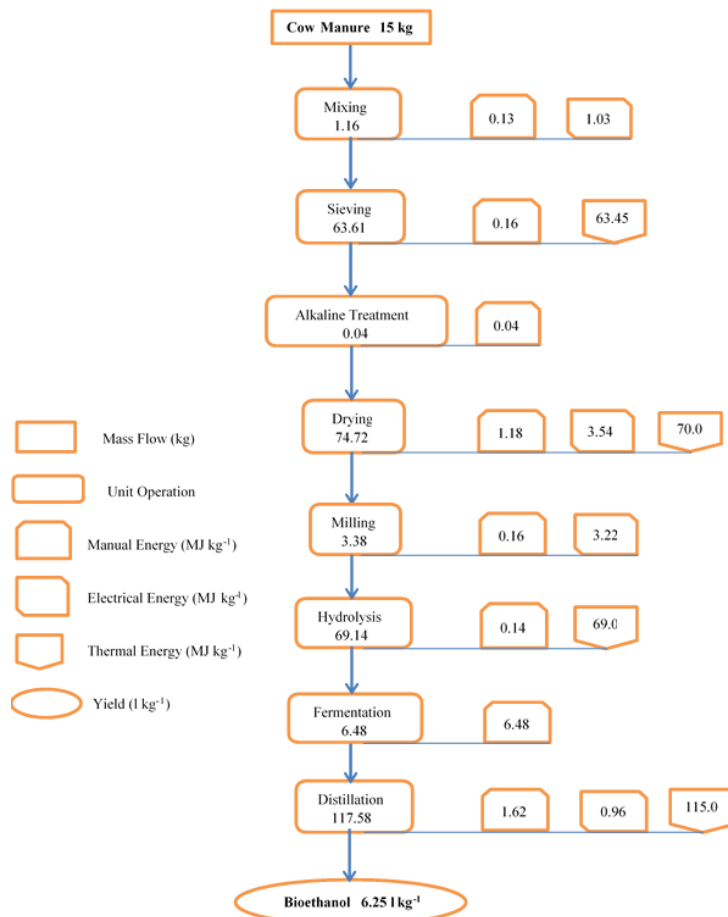


Figure 3 Energy flow diagram for converting 15 kg of cow manure into bioethanol

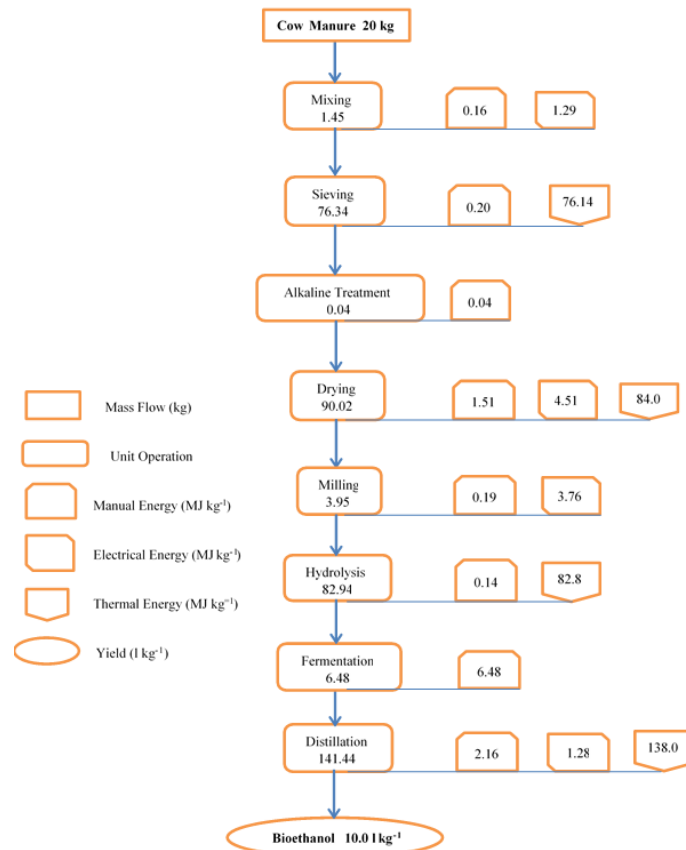


Figure 4 Energy flow diagram for converting 20 kg of cow manure into bioethanol

Table 4 Analysis of variance for energy inputs in converting 10, 15 and 20 kg of cow manure into bioethanol

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------|----------------|----------------|----|-------------|---------|------|
| Manual energy | Between groups | 101.467 | 7 | 14.495 | 277.622 | .000 |
| | Within groups | .835 | 16 | .052 | | |
| | Total | 102.303 | 23 | | | |
| Electrical energy | Between groups | 16.799 | 3 | 5.600 | 14.301 | .001 |
| | Within groups | 3.132 | 8 | .392 | | |
| | Total | 19.932 | 11 | | | |
| Thermal energy | Between groups | 5154.831 | 3 | 1718.277 | 6.385 | .016 |
| | Within groups | 2152.952 | 8 | 269.119 | | |
| | Total | 7307.783 | 11 | | | |

Note: *Significant at $P < 0.05$

3.2 Energy Indicators in converting cow manure into bioethanol

As shown in Table 5, the energy outputs from 4.0, 6.25, and 10.0 litres of ethanol produced from 10, 15, and 20 kg of cow manure were 94.4, 147.5, and 236.0 MJ kg⁻¹, respectively. It can be observed that the energy outputs increase with the quantity of manure loaded and the yield (ethanol) obtained. The energy outputs are lower than energy inputs of 269.37, 336.12 and 402.65 MJ kg⁻¹ obtained. This indicates that more energy input was needed to produce ethanol from the quantity of substrates used. Similar findings by Bamgboye and Kosemani (2018) of 28,431.95 MJ ha⁻¹ was obtained for ethanol production from cassava, where the energy output was also lower than the energy input.

The energy ratios were 0.350, 0.4388, and 0.5861, respectively. This shows high intensive use of energy inputs in the bioethanol production. The energy ratios increase with the quantity of manure loaded and the yield (ethanol) obtained. The energy ratios obtained are lower than the energy ratio of 0.74 obtained by Bamgboye and Kosemani (2018) for ethanol production from cassava. The energy productivities

were 0.0148, 0.0186 and 0.0248 MJ kg⁻¹, respectively. This shows that energy was not efficiently used in the bioethanol production. The energy productivities increase with the quantity of manure loaded and the yield (ethanol) obtained. The energy productivities are lower than 0.034 MJ kg⁻¹ obtained by Bamgboye and Kosemani (2018) for production of ethanol from cassava.

The net energies were -174.97, -188.62 and -166.65 MJ kg⁻¹, respectively. This indicates that ethanol production was not viable with small quantity of manure loaded and yield obtained from energy perspective, but with higher quantity of manure, the net energy would be positive. The net energy values (NEV) were 0.25, 0.16 and 0.10, respectively, which decrease with the quantity of manure loaded and the yield (ethanol). This shows that energy was not efficiently used and the NEV of less than 1.0 implies that ethanol production from cow manure was not viable from energy perspective.

The analysis of variance and Post hoc Test for multiple comparisons (Table 6) showed that there are significant variations in the energy indicators among the unit operations.

Table 5 Energy indicators in the conversion of cow manure into bioethanol

| Feedstock | Yield (litres) | Energy equivalent of ethanol | Energy input | Energy output | Energy ratio | Energy productivity | Net energy | Net energy value (NEV) |
|------------------|----------------|------------------------------|--------------|---------------|--------------|---------------------|------------|------------------------|
| 10 kg Cow manure | 4.0 | 23.6 | 269.37 | 94.40 | 0.350 | 0.0148 | -174.97 | 0.25 |
| 15 kg Cow manure | 6.25 | 23.6 | 336.12 | 147.50 | 0.438 | 0.0186 | -188.62 | 0.16 |
| 20 kg Cow manure | 10.0 | 23.6 | 402.65 | 236.00 | 0.586 | 0.0248 | -166.65 | 0.10 |

Table 6 Analysis of variance and Post hoc Test for energy indicators in converting 10, 15 and 20 kg of cow manure into bioethanol

| (I) Sample | (J) Sample | Mean difference (I-J) | Std. Error | Sig. | 95% Confidence interval | |
|---------------------|---------------------|-----------------------|------------|------|-------------------------|-------------|
| | | | | | Lower bound | Upper bound |
| Energy Input | Energy Output | 176.74667* | 32.79739 | .000 | 105.2873 | 248.2060 |
| | Energy Ratio | 335.58867* | 32.79739 | .000 | 264.1293 | 407.0480 |
| | Energy Productivity | 336.02727* | 32.79739 | .000 | 264.5679 | 407.4866 |
| | Net Energy | 512.79333* | 32.79739 | .000 | 441.3340 | 584.2527 |
| | Net Energy Value | 335.87667* | 32.79739 | .000 | 264.4173 | 407.3360 |
| Energy Output | Energy Input | -176.74667* | 32.79739 | .000 | -248.2060 | -105.2873 |
| | Energy Ratio | 158.84200* | 32.79739 | .000 | 87.3826 | 230.3014 |
| | Energy Productivity | 159.28060* | 32.79739 | .000 | 87.8212 | 230.7400 |
| | Net Energy | 336.04667* | 32.79739 | .000 | 264.5873 | 407.5060 |
| | Net Energy Value | 159.13000* | 32.79739 | .000 | 87.6706 | 230.5894 |
| Energy Ratio | Energy Input | -335.58867* | 32.79739 | .000 | -407.0480 | -264.1293 |
| | Energy Output | -158.84200* | 32.79739 | .000 | -230.3014 | -87.3826 |
| | Energy Productivity | .43860 | 32.79739 | .990 | -71.0208 | 71.8980 |
| | Net Energy | 177.20467* | 32.79739 | .000 | 105.7453 | 248.6640 |
| | Net Energy Value | .28800 | 32.79739 | .993 | -71.1714 | 71.7474 |
| Energy Productivity | Energy Input | -336.02727* | 32.79739 | .000 | -407.4866 | -264.5679 |
| | Energy Output | -159.28060* | 32.79739 | .000 | -230.7400 | -87.8212 |
| | Energy Ratio | -.43860 | 32.79739 | .990 | -71.8980 | 71.0208 |
| | Net Energy | 176.76607* | 32.79739 | .000 | 105.3067 | 248.2254 |
| | Net Energy Value | -.15060 | 32.79739 | .996 | -71.6100 | 71.3088 |
| Net Energy | Energy Input | -512.79333* | 32.79739 | .000 | -584.2527 | -441.3340 |
| | Energy Output | -336.04667* | 32.79739 | .000 | -407.5060 | -264.5873 |
| | Energy Ratio | -177.20467* | 32.79739 | .000 | -248.6640 | -105.7453 |
| | Energy Productivity | -176.76607* | 32.79739 | .000 | -248.2254 | -105.3067 |
| | Net Energy Value | -176.91667* | 32.79739 | .000 | -248.3760 | -105.4573 |
| Net Energy Value | Energy Input | -335.87667* | 32.79739 | .000 | -407.3360 | -264.4173 |
| | Energy Output | -159.13000* | 32.79739 | .000 | -230.5894 | -87.6706 |
| | Energy Ratio | -.28800 | 32.79739 | .993 | -71.7474 | 71.1714 |
| | Energy Productivity | .15060 | 32.79739 | .996 | -71.3088 | 71.6100 |
| | Net Energy | 176.91667* | 32.79739 | .000 | 105.4573 | 248.3760 |

Note: *The mean difference is significant at the 0.05 level.

4 Conclusions

The following conclusions were drawn from this study:

A research was conducted to evaluate the energy consumption in the unit operations of the bioethanol production from cow manure.

Series of energy equations for all the unit

operations were used to analyze the energy consumption in the bioethanol production.

The total energy inputs in converting 10, 15 and 20 kg of cow manure into bioethanol were 269.37, 336.12 and 402.65 MJ kg⁻¹, respectively.

The energy analysis showed that manual, electricity and fuel (petrol, charcoal, gas) were the major types of energy sources available to ethanol

producers locally.

Sieving, drying, hydrolysis and distillation were the major energy intensive operations during bioethanol production, accounting for over 96% of total energy consumption.

Thermal energy, representing over 94% of total energy consumption, was mostly used in all the bioethanol production stages, followed by manual and electrical energies.

It can be established that industrial operation depends largely on all the energy forms to perform optimally, especially manual energy being the fundamental energy for various operations.

The ethanol production from cow manure was not viable from energy perspectives, as net energy value was less than 1.0.

Acknowledgments

The authors would like to appreciate the Department of Agricultural and Environmental Engineering, University of Ibadan, Ibadan, Nigeria and Department of Agricultural and Bio-Environmental Engineering, Federal College of Agriculture, Ibadan, Nigeria for their supports.

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