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Selection of Materials and Formulation of Mathematical Equations for the Design and Construction of a Metal Biogas Plant for Research Purposes

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Abstract: *A mobile biogas plant was designed, constructed and tested for experimental studies following the standard techniques in literatures. The plant was constructed using mild steel AISI 1020 grade material while biodegradable wastes (cattle, pig, poultry and human) were used as the design parameters. However, the research work was primarily conducted to come up with mathematical detail design of biogas energy production system to get clean biogas for domestic use. This involves the development and analyses of the components and body shapes to have a portable and movable system. The major components of the plant are biodigester, biogas storage tank, compressor, electric motor, filter, connecting rubber pipes and steel frame. The physical properties (such as pressure, mass, density, stress, force and volume) of both the steel and biodegradable wastes were analyzed and evaluated. The volume of biogas estimated as 0.0270 m^3/day was considered as main parameter for the design of metal biodigester and biogas storage tank. The quantity of waste for cattle, pig, poultry and human was calculated as 1.080, 0.600, 0.360 and 1.080kg/day respectively. The average wastes needed for the design became 0.780 kg/day with 2.340 kg total mass of water. The volume and density of waste slurry gave $2.3070\times10^{-3}m^3$/day and $1.0143\times10^3kg/m^3$ respectively. The volume, diameter, height and thickness of the biodigester gave $0.0865m^3$, 0.4345m, 0.550m and 0.0028m respectively, while the volume of fermentation chamber was $0.0595m^3$. Factors (such as forces, power, torque, stress, linear and angular velocities) associated with the design calculations were considered. Pressure analysis was carried out in order to determine the expected pressure of gas in the system. The slurry pressure, slurry height, total pressure and biogas pressure gave $3992.8496N/m^2$, 0.4013m, $4.4697\times10^6N/m^2$, and $4.4657\times10^6N/m^2$ respectively. Equations were derived for the biodigester cover plate and 8 was obtained as the required number of bolts and nuts with corresponding core diameters of 13.546 and 13.835mm respectively. It is hypothesized that the use of metal materials in the design and construction of biogas plants will result in improved efficiency and cost-effectiveness compared to traditional methods.*

KEYWORDS: *Mild Steel, Materials Selection, Design, Construction, Biogas Plant, Biodegradable Wastes*

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I INTRODUCTION

Animal agriculture products, such as poultry droppings, cattle dung, pig dung, and other biodegradable wastes (plant husks for rice, maize, or cowpea), pose a threat to the environment and people nearby where they are dumped. Researchers discovered that these biodegradable wastes contain exploitable biogas, which can be obtained through anaerobic digestion and used as a source of energy in the household [1] [2]. Meanwhile, the biogas industry has expanded significantly in recent years, with biogas plants gaining popularity due to their ability to generate renewable energy. The system and its resources are essential features for household waste management and energy needs [3]. Biogas production from waste is one of many alternative sources of renewable energy that are attracting the attention of researchers and energy stakeholders in order to address climate change issues. However, biogas generation from waste under anaerobic conditions has received much attention over the last decades due to the availability of raw materials and environmental compatibility [4] [2]. Although a number of biodigesters have been designed, built, and used for many years [2], which are classified in several ways depending upon the mode of operations and materials of construction [5]. Depending on materials of construction [5], biogas plant is classified as metal, plastic, concrete and fiber glass reinforced. Most biogas plants capable of providing domestic energy needs are bulky and fixed underground [3] [2], which can result to poor maintenance and deterioration of the system [6]. There is need to design an efficient and portable means of providing domestic energy that would be reliable, functional and safe to handle. This work, therefore, focuses on improving the energy production system especially in the area of design and materials selection for optimal results. The aim of this research is to identify the optimal materials and mathematical equations for the design and construction of metal biogas plants. The system will be designed and constructed with mild steel AISI 1020 grade. Cattle, pig, poultry and human wastes will be considered as the main input materials and design parameters for the biodigester and gas storage tank. Other components of the plant includes; pressure gauge that monitors and controls the biogas pressure in the system, rollers, iron body frame provides the plant with rigid support, substrate mixer ensures proper mixing of the waste, hose/pipe for passage of gas to the storage tank, brass ball valve controls the outflow of the digested waste, compressor takes in the generated biogas from biodigester to the storage tank with the help of electric motor. The work took into account the pressure and operations of these components, as well as the design and dimensions of the plant in order to minimize size, weight, and material cost.

II METHODOLOGY

A. Design Consideration, Assumptions and Dimensions

Since the biogas plant is a mini pilot system, the design can be based on reduced capacity of the existing systems. Therefore, the biogas volume is the main parameter that will be considered for the design of the biodigester and gas storage tank.

B. Data Collection

The following data are required for the design as outlined in literatures [1], [7]. In addition, the design procedure used by the following researchers was adopted [3], [8], [9], [10].

i. Biogas production prospects of some common wastes
ii. Densities of biodegradable wastes as feed materials.
iii. Hydraulic retention time (HRT) of 30 days

C. Determination of Mass of Slurry

According to the literature, the daily energy requirement for cooking is estimated at 0.0270 m^3 of biogas per person [1]. To estimate the amount of waste required for cattle, pig, poultry, and human wastes, divide 0.0270 m^3/day by each of the biogas yield per kg input of waste (m^3/kg). Thus, quantity of castle waste = 1.080 kg/day, pig waste = 0.600 kg/day, poultry waste = 0.360 kg/day, human waste = 1.080 kg/day. The average wastes needed = 0.780 kg/day. Using 1:2 as the mass ratio of waste and water. Therefore, mass of water becomes 1.56 kg/day. The total mass of slurry needed per day becomes, $M_S = 0.780 + 1.560 = 2.340$ kg/day

D. Determination of Slurry Volume

The minimum active slurry is that volume which is generally retained in biodigester and that contributes for continuous biogas generation [7]. The volume of slurry is derived from equation (1) [4];

$$V_s = V_{ws} + V_w = \frac{M_{ws}}{D_{ws}} + \frac{M_w}{D_w} \quad (1)$$

where, V_S = daily slurry volume (m^3/day), V_{ws} = Volume of dry waste (m^3); V_w = volume of water (m^3), M_w = Mass of water (kg/day); D_w = density of water (1000 kg/m^3)

,

D_{ws} = Density of dry waste = 1044.166 kg/m^3 , D_S = density of slurry (unknown), M_{ws} = mass of dry waste = 0.780kg/day

$$\therefore V_S = \frac{0.780\ \text{kg/day}}{1044.166\ \text{kg/m}^3} + \frac{1.560\ \text{kg/day}}{1000\ \text{kg/m}^3} = 2.3070 \times 10^{-3}\ \text{m}^3/\text{day}$$

$$D_s = \frac{M_s}{V_s} \qquad (2)$$

Substituting the values of M_s and V_s into equation (2), $\therefore$ Density of slurry, $D_S = 1.0143 \times 10^3\ \text{kg/m}^3$

E. Biodigester Capacity

The total volume of the biodigester V_d, which consists of cylindrical and conical shapes will be determined with equation (3), where; V_S = volume of daily slurry charge, HRT = hydraulic retention time [11].

$$V_d = \frac{V_s \times \text{HRT}}{0.8} \qquad (3)$$

$\therefore$ biodigester volume, $V_d = \frac{V_s \times \text{HRT}}{0.8} = \frac{2.3070 \times 10^{-3}\ \text{m}^3/\text{day} \times 30\ \text{days}}{0.8} =$ 0.0865 m^3 (86.5 liters)

F. Diameter of Biodigester

Having determined the total volume of the biodigester (V_d), the diameter (D_d), height of cylindrical section (H) and height of conical part (h) will be calculated using equation (3.4). Where, V_1 = volume of cylindrical part, V_1 = volume of conical bottom.

$$V_d = V_1 + V_2 = \left(\frac{1}{4} \times \pi \times D_d^2 \times H\right) + \left(\frac{1}{3} \times \pi \times R^2 \times h\right) \qquad (4)$$

Hence, 0.0865 $\text{m}^3 = \{\frac{1}{4} \times 3.1416 \times D_d^2 \times 0.550\ \text{m}\} + \{\frac{1}{3} \times 3.1416 \times \frac{D_d^2}{4} \times 0.1\ \text{m}\}$

0.0865$\text{m}^3 = \{0.4320 D_d^2\} + \{0.0262 D_d^2\}$;

$\therefore D_d^2 = 0.1888$, Biodigester diameter, $D_d = 0.4345$ m (434.5 mm)

G. Volume of Fermentation Chamber

The volume of fermentation chamber (V_f) may be determined by the given expression in equation (5). Where, V_g = volume of daily biogas production, V_d = 0.0865 m^3

$$V_f = V_d - V_g \qquad (5)$$

Hence, volume of fermentation chamber, V_f = 0.0865 – 0.0270 = 0.0595 m^3 (59.5 liters)

H. Thickness of Biodigester

The mild steel AISI 1020 (cold drawn) with yield strength of 350 MPa, 420 MPa tensile strength and 15% ductility was chosen for the construction due to its pressure, temperature and corrosion resistant [12]. Hence, the thickness will be calculated by adopting the procedures outlined by equation (6) [13] [14].

Where, design stress factor, $F = \left[0.65 \left({}^{R_{eg}}/_{R_{mg}}\right)^{-1}\right]$

R_{mg} = minimum tensile strength, P_h = hydraulic test pressure = 40, R_{eg} = minimum yield strength,

R_{eg} = minimum guaranteed yield strength.

$$t = \frac{D_d}{2} \times \left(1 - \sqrt{\frac{10 \times F \times R_{eg} - \sqrt{3} \times P_h}{10 \times F \times R_{eg}}}\right) \qquad (6)$$

$$F = 0.78;\ \square\ \text{thickness}, t = \frac{434.5}{2} \times \left(1 - \sqrt{\frac{10 \times 0.78 \times 350 - \sqrt{3} \times 40}{10 \times 0.78 \times 350}}\right) = 2.7744\ \text{mm}\ (\approx 3\ \text{mm})$$

This implies that a steel plate of 3 mm thickness (14 gauge) may be used for fabrication, and according to Budinski [12], steel plate thickness of 2 mm and above are generally recommended for pressure vessels.

I. Substrate Mixer

The mild steel AISI 1020 material that was chosen for the design will be used throughout the plant. The major factors that will be considered for the mixer are; the stirrer shaft diameter (D), power to be transmitted by the shaft (P), total force to resist the stirring (F), length (L) and width of blades (W), shear stress (τ) and torque (T). Since the mixer will be designed for manual operations, it will be subjected to a torque. The design stress in shear for a steel shaft and its diameter is given by equation (7) [9] [15]:

$$\tau = \frac{16 \times T}{\pi \times D^3}, \qquad \therefore D = \sqrt[3]{\frac{16 \times T}{\pi \times \tau}} \qquad (7)$$

The power that can be transmitted by the shaft from human effort (P) and linear velocity, V (m/s) are given by equations (8) and (9) respectively [8]. Where; N = speed of shaft (rpm), w = angular speed (rad/s)

$$P = \frac{2\pi \times N \times T}{60} = F \times V \qquad (8)$$

$$V = w \times L = \left(\frac{2\pi \times N}{60}\right) \times L \qquad (9)$$

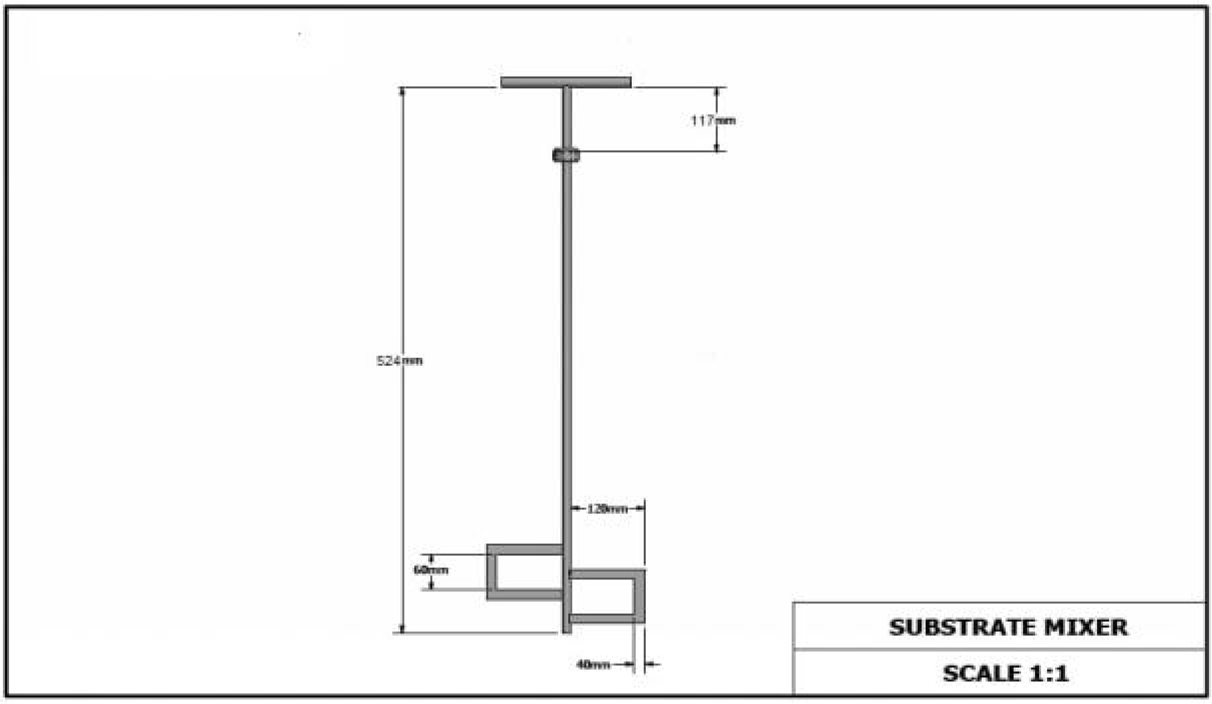


Fig.1: The substrate mixer

J. Substrate Mixer Blades

The substrate mixer was designed with six blades of varying lengths and width. This ensures proper stirring and mixing of waste slurries, prevents solidification of the upper part, and prevents scum from forming on the slurry's surface. The areas of the substrate mixer blades can be calculated as thus; for plates 1, 2, 3, 4; length = 0.180 m while width = 0.060 m. Hence, area of plates 1, 2, 3, 4 = 0.108m^2 with ratio of length to width of 3.0. For plates 5, 6; length = 0.080 m while width = 0.060 m. Hence, area of plates 5, 6 = 0.0048m^2 with ratio of length to width of 1.33. Because the waste in the biodigester will be stirred manually by human efforts, thus the speed of the stirrer, N = 45 rpm [3] [11].

$$\therefore \text{ Linear velocity, } V = \left(\frac{2 \times \pi \times 45 \text{ rpm}}{60}\right) \times 0.180 = 0.8482 \text{ m/s} .$$

III. PRESSURE AND FORCE ANALYSES

A. Force Analysis on Substrate Mixer

Consider the forces associated with the mixer, which are drag and lift forces. A body experiences a net force, (F_n) when in relative motion with a liquid [16]. The net force has two components; the drag force (F_d) which resists mixer's motion, and lift force (F_L) which exerts force as slurry flows around. Hence, F_d, which is proportional to half density (kg/m^3), area, velocity squared (m/s) and drag coefficiency (C_d) may be calculated using equation (10) [17] [18]:

$$F_d = \frac{1}{2} \times \rho \times V^2 \times A \times C_d \tag{10}$$

Considering the length to width ratios of both plates, $F_{d(1,2,3,4)} = 1.11$ whereas, $F_{d(5,\ 6)} = 1.11$. Hence the sum of F_d for both plates may be calculated using equation (10) [18]:

$$F_{d(1,2,3,4)} = 4 \times \left\{\frac{1}{2} \times 1.0143 \times 10^3 \times (0.8482)^2 \times 1.08 \times 10^{-2} \times 1.11\right\} = 17.4960 \text{ N}$$

$$F_{d(5,\ 6)} = 2 \times \left\{\frac{1}{2} \times 1.0143 \times 10^3 \times (0.8482)^2 \times 4.80 \times 10^{-3} \times 1.07\right\} = 3.7479 \text{ N}$$

Since the total area of the blades is greater than surface area of the mixer shaft, this implies that the F_d due to the surface area of the mixer in waste will be 10% the sum of the total F_d on the plates.

Hence, $F_{d(shaft)} = 0.1 \times 21.2439 = 2.1244$ N; ▪ $F_{d(overall)} = 23.3683$ N

Taking into account the losses in the analytical approach used in the calculation, let the maximum force that the mixer must overcome be 25 N. Therefore, power transmitted, $P = F \times V = 25 \times 0.8482 = 21.2050$ W.

Hence, the shaft torque (T) can be obtained; $T = \frac{60 \times P}{2\pi \times N} = \frac{60 \times 21.2050 \text{ W}}{2 \times 3.1416 \times 45 \text{ rpm}} = 4.4998$ Nm

B. Diameter of Mixer Shaft

When designing machine parts, it is desirable to keep the design stress, σ_d (MPa) lower than the maximum stress at which failure of the material takes place [10]. In case of ductile materials, where the yield point is clearly defined, the factor of safety (S_f) is based upon the yield stress (σ_y). In such cases, σ_d and mean σ_d in shear may be calculated as defined by equation (11) [8]:

$$\sigma_d = \frac{\sigma_y}{S_f} = 2\tau \tag{11}$$

The material, type of stress, service conditions, shape of the parts, and other factors all play a role in determining the factor of safety for design [9]. Khurmi et al. [8], suggested values of S_f of 4 for steel on steady load, 8 for steel on live load and 12 to 16 for steel on shock load. Hence, S_f of 8 will be considered for the design.

Therefore, $\text{design stress}, \sigma_d = \frac{350 \text{ MPa}}{8} = 43.75 \text{ MP};, \text{where shear stress}, \tau = 21.875 \text{ MPa}$

$$= \sqrt[3]{\frac{16 \times T}{\pi \times \tau}} = \sqrt[3]{\frac{16 \times 4.4998 \text{ Nm}}{3.1416 \times 21.875 \times 10^6}} = 10.20 \text{ mm}$$

$\therefore \text{Shaft diameter}, D$.

This implies that a shaft of diameter 11 mm may be used for construction.

C. Gas Pressure

The biogas is a product from the fermentation process of anaerobic digestion, and as the pressure rises, the concentration also rises. The sealed biogas in the system will continue building pressure until fermentation ceases. However, the maximum pressure that can be reached before fermentation ceases is known as total pressure, P_t [7], and the main variables associated with these are volume and density [5]. The biogas pressure (P_g), total pressure in the system (P_t) and the pressure due to the slurry (P_s) associated with system will be calculated [10] [15].

$$P_g = P_t - P_s = \left(\frac{2 \times t \times \tau}{r}\right) - (\rho \times g \times h) \tag{12}$$

Where; $P_s =$ pressure due to slurry (N/m^2), $\rho =$ density of slurry (kg/m^3), $h_f = \text{height of slurry}, r = \text{radius}$

Pressure tanks, according to their dimensions may be classified as thin or thick shell. If the wall thickness, t is less than 0.1 of the diameter, D then it is called a thin shell tank. On the other hand, if the wall thickness is greater than 0.1 of the D, then it is called thick shell tank [9] [10]. Since the biodigester thickness is less than 0.1 of the diameter, we shall treat it as thin shell.

$$V_F = \left\{\frac{1}{4} \times \pi \times D_d^2 \times h_f\right\} + \left\{\frac{1}{3} \times \pi \times \frac{D_d^2}{4} \times h\right\} \tag{13}$$

$V_f = \text{volume of fermentation chamber} = 0.0595$, $h_f =$ height of slurry, $\tau =$ maximum shear stress

$\therefore 0.0595 = \left\{\frac{1}{4} \times 3.1416 \times (0.4345)^2 \times h_f\right\} + \left\{\frac{1}{3} \times 3.1416 \times \frac{0.4345^2}{4} \times 0.1\right\},$ $h_f = 0.4013$ m

$P_s = \rho \times g \times h_f = 1.0143 \times 10^3 \times 9.81 \times 0.4013 = 3992.8496$ N/m^2, ▪ $\tau = \frac{\sigma_y}{2} = \frac{350 \text{ MPa}}{2} = 175$ MPa

$\therefore \text{total pressur}, P_t = \frac{2 \times 2.7744 \times 10^{-3} \text{ m} \times 175 \times 10^6 \text{ N/m}^2}{2.1725 \times 10^{-1} \text{ m}} = 4.4697 \times 10^6$ N/m^2, $\therefore \text{biogas pressure}, P_g = 4.4657$ N/mm^2

D. Biodigester Cover

The biodigester's cylindrical cover will be secured with bolts, nuts, and thick gaskets to ensure joint tightness, gas-tightness, and resistance to the upward force exerted by gas pressure. A pressure gauge will also be fixed at the cover to monitor and control the biogas pressure in the system. The design equations will be derived using the following mathematical symbols: D_f = Diameter of the biodigester mouth where the plate covers, N_b = Number of bolts for the cover, $D_c =$ Core diameter, $\sigma_{th} =$ Permissible tensile stress (N/mm^2), F_r = Resisting force, S_b = Circumferential pitch of the bolt (inter bolts spacing), D_h = Diameter of the bolt hole, D_P = Pitch circle diameter (distance between any two opposite bolts center to center), $t_o =$ Overall thickness of cover plate, $D_o =$ Outside diameter of the system cover plate. Table 1 displays the design dimensions of screw threads, bolts, and nuts for the coarse series [8].

Table 1: Design dimensions of screw threads, bolts and nuts for coarse series

Coarse series	**Pitch (mm)**	**Major or nominal diameter Nut and Bolt (d = D) in mm**	**Effective or pitch diameter Nut & Bolt (**	**Minor or core diameter D_C (mm)**	**Depth of thread (bolt) in**	**Stress area (mm^2)**

			D_p)	**Bolt**	**Nut**	**mm**	
M 7	1	7.000	6.350	5.773	5.918	0.613	28.9
M 8	1.25	8.000	7.188	6.466	6.647	0.767	36.6
M 10	1.5	10.000	9.026	8.160	8.876	0.920	58.3
M 12	1.75	12.000	10.863	9.858	10.106	1.074	84.0
M 14	2	14.000	12.701	11.546	11.835	1.227	115
M 16	2	16.000	14.701	13.546	13.835	1.227	157
M 18	2.5	18.000	16.376	14.933	15.294	1.534	192
M 20	2.5	20.000	18.376	16.933	17.294	1.534	245
M 22	2.5	22.000	20.376	18.933	19.294	1.534	303

E. Design of bolt for the Cover

Let the upward force acting on the biodigester cover be represented by equation (14) [8] [9];

$$F_g = \frac{\pi \times D^2 \times P_t}{4} \quad (14)$$

Therefore, the upward force due to biogas (F_g) must be resisted by the bolts fixed at cover to ensure gastight condition at all times. Let the resisting force offered by the bolts be F_r. [8]. This implies that F_g acting on the cover due to biogas must be equal to the resisting force (F_r) offered by the number of bolts.

$$\square \ F_r = \frac{\pi \times D_c^2 \times \sigma_{th} \times N_b}{4} \quad (15)$$

$$\text{This implies that; } \frac{\pi \times D_f^2 \times P_t}{4} = \frac{\pi \times D_c^2 \times \sigma_{th} \times N_b}{4}; \ \therefore D_f^2 \times P_t = D_c^2 \times \sigma_{th} \times N_b$$

$$\text{Hence, number of bolts, } N_b = \frac{D_f^2 \times P_t}{D_c^2 \times \sigma_{th}}$$

Therefore, if the value of number of bolts (N_b) as given by the equation is odd or fraction, then the next higher even number is adopted. Hence, still using MS AISI 1020 as the design material, $\sigma_y =$ 350 MPa, S_f= 4, σ_{th} can be calculated [8] [10].

$$\sigma_{th} = \frac{\sigma_y}{S_f} \quad (16)$$

$$\therefore \text{Permissible tensile stress, } \sigma_{th} = \frac{350 \text{ MPa}}{4} = 87.50 \text{ MPa } (87.50 \text{ Nmm}^2)$$

Therefore, considering the presence of gasket seal (10 mm thick) that will increase the overall cover plate thickness, the bolt nominal diameter becomes 16 mm with D_f as 160 mm while the lower and upper plate thickness remains 3 mm as calculated earlier. The corresponding core diameter (D_C) of the bolt and nut therefore becomes 13.546 and 13.835 mm respectively as illustrated in literatures [8] [9] [10].

$$N_b = \frac{D_f^2 \times P_t}{D_c^2 \times \sigma_{th}} = \frac{160^2 \text{ mm} \times 4.4657 \text{ MPa}}{(13.546)^2 \text{ mm} \times 87.50 \text{ MPa}} \therefore N_b = 7.1203 \text{ (8 bolts will be used)}$$

F Design of Cover Plate

The cover plate's tightness is determined by the bolts' circumferential pitch. Therefore, to ensure gas-tightness, the circumferential pitch of the bolts S_b, should be between $20\sqrt{D_h}$ (i.e. minimum circumferential pitch of the bolts) to $30\sqrt{D_h}$ (i.e. maximum circumferential pitch of the bolts). Since the nominal diameter of the bolt is 14 mm, this implies that the hole diameter (D_h) is 15 mm whereas the overall thickness (t_o) is 16 mm [8].

$$D_P = D_f + 2t_o + 3D_h \tag{17}$$

$$D_o = D_P + 3D_h = D_f + 2t_o + 6D_h \tag{18}$$

$$\therefore D_P = 160 + 2(16) + 3(15) = 237 \text{ mm}$$
$$\therefore D_o = 160 + 2(16) + 6(15) = 282 \text{ mm}$$
$$⊡ \text{ circumferential pitch of the bolts, } S_b = \frac{\pi \times D_p}{N_b} = \frac{3.1416 \times 237}{8} = 93.0697 \text{ mm}$$

Therefore, minimum and maximum circumferential pitch of the bolts may be calculated as follows:

$$S_{b1} = 20\sqrt{D_h} = 20\sqrt{15} = 77.4597 \text{ mm}$$
$$S_{b2} = 30\sqrt{D_h} = 30\sqrt{15} = 116.1895 \text{ mm}$$

Thus, since the circumferential pitch of the bolts (S_b) obtained above lies within 77.4597 mm to 116.1895 mm, size of the bolt chosen is satisfactory. Hence, the size of the bolt is M14. As a result, the same design procedures were used for the biogas storage tank. The research work took into account the design calculations for each component, including the electric motor and compressor, as well as the plant's overall operations. Fig. 2 depicts the cover plate, including design specifications and dimensions.

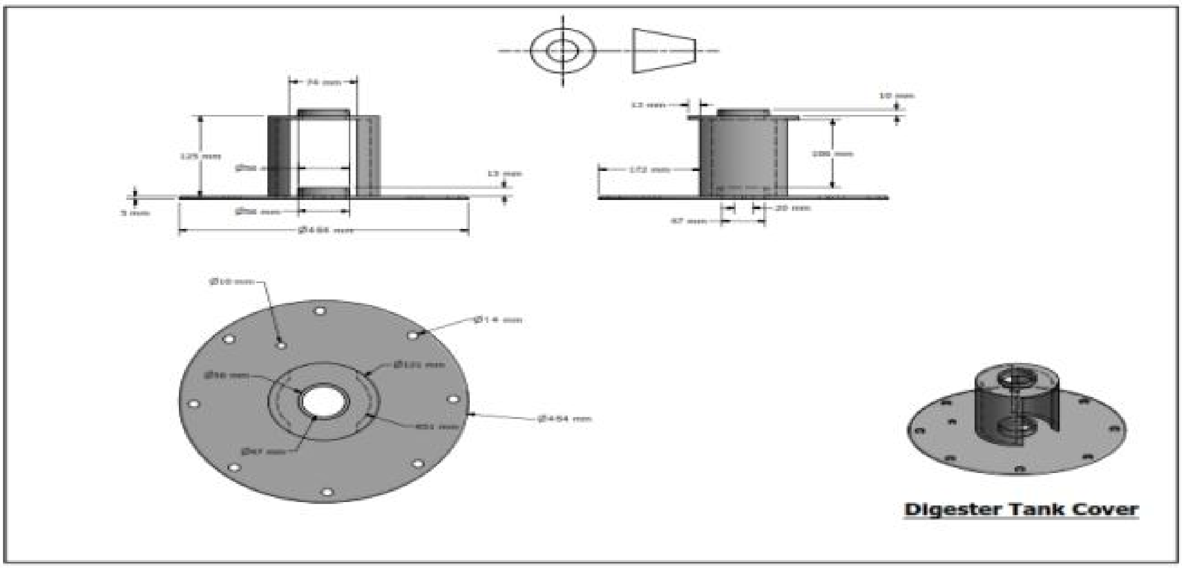


Fig.2: Biodigester tank cover

IV OVERVIEW MATERIALS FOR CONSTRUCTION

Given the relatively long hydraulic retention time of biodegradable waste inside the biodigester during the anaerobic digestion process, material selection for system construction is critical for achieving optimal plant performance. Materials were chosen based on cost, availability, corrosion resistance, and environmental factors. Corrosive elements such as H_2S, CO_2, NH_3, moisture, Mg, Ca, and water vapor are unavoidable byproducts of biodegradable wastes that are commonly produced during the anaerobic digestion process. The slurry level will not be constant at all times, which is a good thing because the transition from slurry to gas is prone to corrosion. When proper materials are chosen during the design and construction stages to prevent corrosion, a significant amount of money can be saved on maintenance and material replacement. Simple shape changes or the application of corrosion-resistant coatings can prevent the plant from shutting down entirely. The tanks are best made round to prevent dirt accumulation in corners, and the entire system has been coated because almost all of the plant's metallic components come into contact with the corrosive waste contents during operation. The biodigester and storage tank were designed so that no sludge or waste remained in the system after it was drained. The tank walls were insulated with protective coatings to prevent heat loss, particularly at night. On the other hand, it must be possible to allow radiation to heat the mixture content in order to achieve and maintain the desired temperature; this will occur primarily through the top of the biodigester or gas storage tank. When selecting a material for the plant, several parameters were considered, including insulation value, corrosion resistance, lifetime, waterproofness, and gas-tightness. The use of appropriate materials and strategies can significantly extend the life of biogas plant materials while lowering the risk of corrosion, wear, and mechanical impact damage. As a result, material selection is critical for ensuring a system's long service life in corrosive environments and avoiding damage during or after operation. Table 2 displays the mechanical properties of alloy steel materials in which steel alloy 1020 (cold drawn) was used in the design [19]. Table 3 shows the summary of materials for the construction of the biodigester and gas storage tank as outlined in the literatures [20], [21], [22], [23], [24].

Table 2: Mechanical properties of alloy steel materials

Material/Condition	**Yield Strength (σ_y) (MPa [KSi])**	**Tensile Strength (σ_t) (MPa [KSi])**	**Ductility (% Elongation)**
Steel alloy A36			
• Hot rolled	220–250 (32–36)	400–500 (58–72.5)	23
Steel alloy 1020			
• Hot rolled	210 (30)	380 (55)	25
• Cold drawn	350 (51)	420 (61)	15
• Annealed (870 °C)	295 (42.8)	395 (57.3)	36.5
• Normalized (925 °C)	345 (50.3)	440 (64)	38.5
Steel alloy 1040			
• Hot rolled	290 (42)	520 (76)	18
• Cold drawn	490 (71)	590 (85)	12
• Annealed (785 °C)	355 (51.3)	520 (75.3)	30.2
• Normalized (900 °C)	375 (54.3)	590 (85)	28.0
Steel alloy 4140			
• Annealed (815 °C)	417 (60.5)	655 (95)	25.7
• Normalized (870°C)	655 (95)	1020 (148)	17.7
• Oil-quenched and tempered (315°C)	1570 (228)	1720 (255)	11.5
Steel alloy 4340			
• Annealed (810 °C)	472 (68.5)	745 (108)	22
• Normalized (870°C)	862 (125)	1280 (185.5)	12.2
• Oil-quenched and tempered (315 °C)	1620 (235)	1760 (255)	12

Table 3: Overview materials for construction of digesters and gas storage tanks

Materials	**Corrosion resistant**	**Preparation tank**	**Residue storage Tank**	**Biogas storage tank**
Reinforced concrete	Excellent	Suitable	Suitable	Not suitable
Plastics	Excellent	Suitable	Suitable	Suitable
Fiber-glass reinforced plastic	Excellent	Suitable	Suitable	Suitable
Bricks	Excellent	Suitable	Suitable	Not suitable
Coated mild steel	Excellent	Suitable	Suitable	Suitable
Stainless steel (SS)	Excellent	Suitable	Suitable	Suitable

V. DESCRIPTION OF THE PLANT

All of the plant's parts and systems were built and assembled using standard techniques described in the literature. The plant's main components include a biodigester tank, gas storage system, compressor, electric motor, valves, pressure gauge, filter units, and a supporting frame.

Biodigester: The biodigester tank is a cylindrical container with a volume of approximately 86.5 liters (0.0865 m^3) that holds both the substrate and the biogas produced. According to the design calculations, the diameter is 0.4345 m (434.5 mm), the height is 0.650 m (650 mm), and the fermentation chamber volume is 0.0595 m^3 (59.5 liters). The tank was built with cold drawn medium carbon steel alloy AISI 1020, as shown in Table 2 [19]. Two holes were drilled into the container, one in the front and one in the back. Each of these holes has a different diameter and purpose. The container's back opening, which measures 50 mm in diameter, will serve as an outlet for the digested waste. The second opening, with a diameter of 10 mm, will be connected to a compressor inlet hose and serve as an outlet for the biogas produced. The base and outlet of the biodigester will be conical in shape to facilitate the outflow of the digested slurry after digestion. The biodigester cover will be tightly sealed with a gasket to ensure an airtight digester and prevent biogas leakage into the ambient air.

Biogas Storage Tank: The biogas produced during anaerobic digestion is compressed and stored in the storage tank. As the gas formation process begins, the gas expands and rises to the top of the biodigester, where the compressor forces it out through the gas regulator. Here, the gas holder has a capacity of 23.6 liters and a diameter of 197 mm. The tank's contents will need to be heated by radiation, so the tank was coated with heat-resistant coatings.

Gas Outlet Valve: The compressor takes the biogas from the gas storage tank through the outlet control valve. The valve regulator is made of brass and opens when in use.

Ball Valves: Three ball valves made of brass were used. The first valve was installed on the biodigester tank's outlet gas pipe. To control the outflow of the digested slurry, the second valve will be installed at the back of the biodigester tank and connected to 60 mm diameter PVC pipe. The third valve was installed at the gas storage tank to regulate gas delivery to the tank.

Substrate Mixer: A substrate mixer (stirrer shaft) was installed to ensure the slurry is properly mixed for effective gas formation. This consists of a turning shaft with blades that are moved by bearings that convert the circular motion of human efforts into the shaft's rotary motion. The shaft has a diameter of 12 mm and a length of 524 mm, as determined by design calculations, and was designed with six blades of varying lengths and widths. To increase rigidity, the shaft will be inserted into bearings and fixed to a flange on the biodigester cover. The area of plates 1, 2, 3, and 4 is 0.108m^2, with a length-to-width ratio of 3.0. For plates 5, 6, the length is 0.080 m and the width is 0.060 m, with an area of 0.0048 m^2 and a length-to-width ratio of 1.33.

Body Frame: The body frame is made of 1½"×1½"×3.0 mm angle iron. The height is 696 mm; the width is 722.5 mm; and the length is 1020 mm. The frame was designed to support the weight of both the plant components and the slurry in the biodigester and gas tank. It is supported by four rollers, which allows the plant to be moved from one location to another.

Pressure Gauge: Pressure gauge was primarily used to monitor the pressure of produced biogas in the biodigester. It also regulates the biogas pressure in the system and displays it using an analogue pointer.

Scrubbing: The primary function of this scrubbing or filter unit in the plant is to remove some of the corrosive gases that combine with water vapour to form acids and corrode the plant's metal components. The major gases that would be considered here are carbon dioxide (CO_2) and hydrogen sulfide (H_2S). The plant have two filters: a primary and a secondary filter. The primary filter, installed between the biodigester and the compressor, was used to separate CO_2, and the secondary filter, installed between the compressor and the storage tank, was used to separate hydrogen sulphide (H_2S).

Compressor: A compressor is a machine that compresses air at ambient temperature (15°C) and atmospheric pressure (1bar) to a higher pressure, increasing its density, or mass per unit volume. The compressor compresses the biogas produced by the biodigester, increasing the pressure and making it easier to store and transport. The electric motor typically drives the compressor.

Electric Motor: The electric motor drives the biogas plant's components, including the compressor. It is usually connected to a power source like a generator or the electricity. The electric motor and compressor work together to compress and store biogas in a storage tank, creating a sustainable and renewable energy source for households.

VI RESULTS AND DISCUSSIONS

When the biogas plant is operational, the already mixed sample of pig and cattle slurries is introduced into the biodigester tank through the biodigester cover. In the same vein, the slurries inside the biodigester are mixed by a stirrer, which converts rotary motion into circular motion, turning the mixture with human power. The biodigester's outer surface was painted black to make environmental effects more visible, as the dry land ambient temperature is in the 35⁰C range, which corresponds to the mesophilic temperature range required for biodegradation. Figs. 3 and 4 show the plant's orthographic and exploded views, respectively. The plant's main components, as previously discussed, are the biodigester tank, substrate mixer, feeder assembly, gas storage tank, substrate outlet, compressor, electric motor, ball valves, pressure gauge, and steel body frame. The biodigester was filled through the cover with two types of slurry that is made up of animal wastes with water at the ratio of 1:2. The slurry was left to digest for about 24 hours after stirring, and it was stirred at least twice a day to promote biogas production. The corrosion effects of the wastes on the plant's metallic components were noted and will be investigated further research. The system was primarily designed to meet the daily energy requirements of a three or four-person household. For 0.0270 m^3/day of biogas, the amount of waste required for cattle, pigs, poultry, and humans can be calculated by dividing 0.0270 m^3/day by each biogas yield per kg input of waste. Thus, the amount of castle waste = 1.080 kg/day, pig waste = 0.600 kg/day, poultry waste = 0.360 kg/day, and human waste = 1.080 kg/day. As a result, the average waste needed is 0.780 kg per day. Thus, the amount of castle waste = 1.080 kg/day, pig waste = 0.600 kg/day, poultry waste = 0.360 kg/day, and human waste = 1.080 kg/day. As a result, the average waste needed for digestion is 0.780 kg per day. The biogas yield per kg of waste input for cattle, pigs, and humans was 0.025, 0.055, and 0.029 m3/kg, respectively. The daily gas production volume increased steadily, peaking at 0.027m3/kg on the 91st and 98th days, respectively. The biogas yield after 98 days indicates that cattle produced more gas than pig waste.

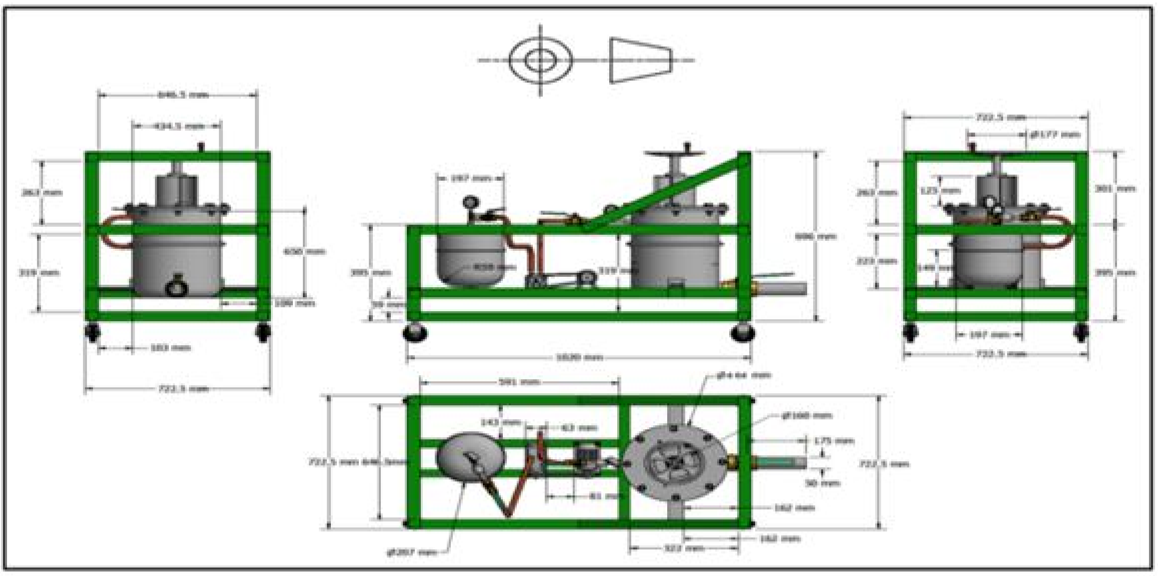
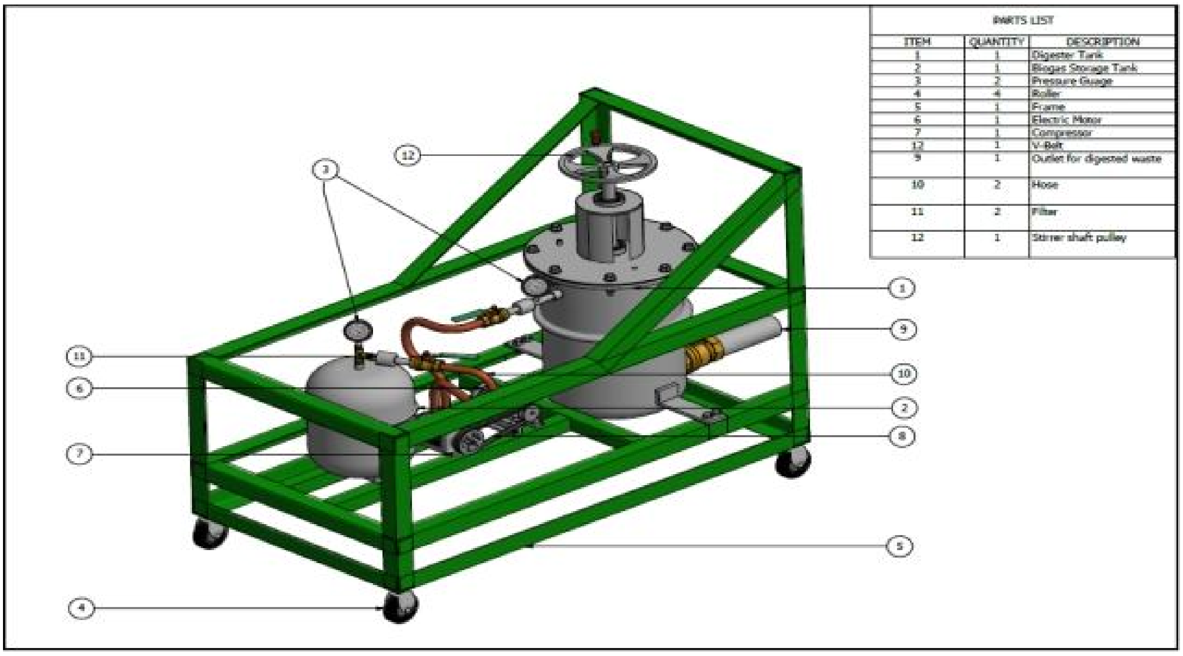


Fig.3: The Exploded View of the Plant



PARTS LIST

ITEM	QUANTITY	DESCRIPTION
1	1	Digester Tank
2	1	Biogas Storage Tank
3	2	Pressure Guage
4	4	Roller
5	1	Frame
6	1	Electric Motor
7	1	Compressor
12	1	V-Belt
9	1	Outlet for digested waste
10	2	Hose
11	2	Filter
12	1	Stirrer shaft pulley

Fig. 4: The biogas plant

The pH Value: The pH range and functions in anaerobic digestion of waste using a steel biodigester are crucial for the efficient production of biogas. The optimum pH range for digestion is typically between 6.6 and 7.6, as this range allows for the optimal activity of the microorganisms involved in the process. Once the pH of the digester falls below 6.7, the interactions between these different groups of microbes become unbalanced and digestion begins to fail. The pH value is one of the major factors influencing the anaerobic digestion performance and final biomass energy yield. In a steel digester, the pH value is influenced by various factors such as the properties of the raw material fed into the digester, the hydraulic retention time (HRT), and the temperature. The pH value can be controlled by adjusting the HRT, temperature, and the amount of raw material fed into the biodigester. The optimal pH range allows for the optimal activity of the microorganisms involved in the process, inhibits the growth of pathogens, improves biogas production, reduces corrosion, and improves system stability.

Temperature: Temperature plays an important role in the anaerobic digestion of biodegradable waste. The optimal temperature range promotes the activity of the microorganisms involved in the process, increases biogas production, reduces corrosion, improves system stability, lowers pathogenic concentration, reduces energy input, and makes the process more scalable. Table 4 shows the temperature and pH values of cattle and pig waste used in the experiments over a 98-day period. We chose to work in mesophilic (20 to 40°C) conditions because maximum methane generation rates are achieved at temperatures ranging from 35°C to 37°C in this system. The temperature in the biodigester can drop due to weather and cold nights, and when this happens on a regular basis, certain measures must be taken to maintain the elevated temperature. More than 40°C can kill mesophilic bacteria, so it should be avoided at all costs. During this time, both ambient and slurry temperatures were in the mesophilic range. Table 4 displays the minimum and maximum ambient temperatures, while slurry temperatures varied with pH value, indicating that slurry temperatures were lower than ambient temperatures in the morning. Meanwhile, slurry temperatures exceeded ambient temperatures in the afternoon. Higher temperatures increase the rate of digestion of the slurry, resulting in increased gas production. The digester residue slurry is dark greenish in colour and can be used as an organic fertilizer for agriculture due to its high nitrogen, phosphorus, and potassium content. The optimal temperature range can help to reduce corrosion in the steel digester by preventing the formation of acidic or alkaline conditions that can damage the steel.

Coating: Coatings are critical in the context of a mild steel biodigester plant because they protect the steel from corrosion and ensure the plant's efficient operation. To improve the corrosion resistance of mild steel materials, a coating is required. Painting increases the material's durability and prevents molecules from penetrating the walls and corroding the steel. The materials' surfaces were first pretreated to ensure that the wall was clean and smooth enough for the protective layer to adhere properly. The importance of surface preparation should not be underestimated. When a coating is applied to a rusted or corrosive metal surface, it will continue to corrode. Coatings were applied on the plant to provide corrosion protection, durability, ease of cleaning, increased efficiency, cost savings, environmental benefits, improved safety, extended lifespan, improved performance, and reduced plant maintenance.

Table 4: Temperature (^{o}C) and pH values of cattle and pig wastes used for the experiments

		Cattle waste		**Pig waste**	
S/N	**Day**	**Temperature (^{O}C)**	**pH value**	**Temperature (^{O}C)**	**pH value**
1	7	24.8	6.04	24.6	6.42
2	14	24.2	5.61	23.7	6.05
3	21	25.5	5.52	25.2	6.02
4	28	24.4	4.32	24.2	5.67
5	35	23.5	4.25	23.5	5.04
6	42	24.7	4.17	24.5	5.15
7	49	25.3	4.09	25.0	4.95
8	56	24.0	3.75	24.4	4.81
9	63	24.6	3.65	24.6	4.50
10	70	23.8	3.45	23.5	4.46
11	77	24.2	3.44	24.0	4.13
12	84	23.5	3.25	23.5	3.92
13	91	24.3	3.20	24.4	3.55
14	98	24.5	3.14	24.6	3.70

VII CONCLUSION

In conclusion, the design and construction of a metal biogas plant for research purposes requires careful selection of materials and the formulation of mathematical equations to ensure optimal performance and efficiency. The materials used in the design of a plant have an impact on its life span; thus, selecting appropriate materials for a metal plant is critical for ensuring its efficiency and longevity. Understanding how to choose and maintain materials for biogas plants is critical for increasing efficiency while reducing environmental impact. The supporting data for this study were gathered through experiments and observations at various biogas plants. Also, regular maintenance is required to ensure the plant's proper operation, which includes cleaning and inspecting the digester, compressor, and other components, as well as performing routine maintenance tasks such as lubricating moving parts. The biogas plant designed and built for this study was effective in producing biogas, and the research found that increasing the concentration of animal slurries resulted in a corresponding increase in biogas. According to the study, more biogas was produced in the afternoon, when ambient and slurry temperatures were at their highest. Also, increasing the concentration of the slurry increases gas production, whereas decreasing the concentration results in lower gas volumes. The waste residue, which is high in nitrogen, phosphorus, and potassium, can be used as an organic fertilizer and soil amendment in agriculture. The future scope of this research includes the application of the developed mathematical equations to the design and construction of larger scale metal biogas plants for commercial use; in-depth research on corrosion in biogas plant systems with the aim of enhancing safety, reliability, and sustainability in industrial operations; investigate the specific corrosion mechanisms that led to the failure of the biogas plant, such as stress corrosion cracking and the impact of caustic chemicals on the system’s structural integrity.

I. REFERENCES

[1] C. E. Okeke, "Renewable Energy Technology Development in Nigeria," in *Paper presented at a National Workshop on Creating Demand and Removing Barriers to Renewable Energy Marked Development in Nigeria*, Sheraton Hotels and Towers Abuja, 2001.

[2] S. I. Eze, A. U. Ofoefule, O. U. Uzodinmma, E. C. Okoroigwe, N. F.Oparaku and O. U. Oparaku, "Characterization and Performance Evaluation of an 11m3 Biogas Plant," *Continental Journal of Renewable Energy* , vol. 2(1), pp. 1-6, 2011.

[3] E. C. Okoroigwe, O. C. Iloeje, S. O. Enibe and J. I. Eze, "Design, Construction and Performance Evaluation of a 1200 liter Plastic Biodigester," *Nigeria Journal of Solar Energy,* vol. 16, pp. 170-186, 2006.

[4] C. Polprasert, "Organic Waste Recycling," IWA Publishing, 2007. Available online at: www.nofa.org/soil/html/table8.php.

[5] R. Dave and B. John, Anaerobic Digestion of Animal Waste: Factors to Consider, UK: ATTRA, Ltd, 2006.

[6] C. J. Olelewe, E. C. Okoroigwe and D. O. N. Obikwelu, "An Investigation of Corrosion and Its Effects on Mild Steel Biodigester Materials by Electrochemical Corrosion Method," *Journal of Inventive Engineering and Technology (JIET): ISSN: 2705-3865,* pp. Volume-5, Issue-2, pp-36-47, 2024.

[7] Y. Vögeli, C. R. Lohri, A. Gallardo, S. Diener and C. Zurbrügg, Anaerobic Digestion of Biowaste in Developing Countries. Practical Information and Case Studies, Dübendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (Eawag), 2014.

[8] R. S. Khurmi and J. K. Gupta, A textbook of Machine Design, New Delhi, India: 14th Edition, EURASIA Publishing House (PVT) LTD, 2005.

[9] C. S. Sharma and K. Purohit, Design of Machine Elements, New Delhi: Prentice Hall of India, 2003.

[10] J. E. Shigley and C. R. Mischke, Mechanical Engineering Design, New Delhi: 5th Edition, McGraw Hill Publication, 1989.

[11] G. D. Rai, Non-Conventional Energy Sources, New Delhi, India: 2nd Edition, Khanna Publishers, 2000.

[12] K. G. Budinski, Engineering Materials, Properties and Selection, New York, USA: New Jersey Publishing Company Inc. A Prentice-Hall Company., 1989.

[13] "ISO 9809-1, Gas cylinders - Refillable seamless steel gas cylinders - Design, construction and testing - Part 1:," Quenched and tempered steel cylinders with tensile strength less than 1100 MPa., Available online at: www.iso.org.

[14] "Technical Information: TI 002, Development of Calculation Formulas for Cylinder Wall Thickness. Issue date: 2018-01-02. Available online at: www.ecma.org".

[15] M. G. James and S. P. Timoshenko, Mechanics of Material, USA: 4th Edition, PWS Publishing Company, 1997.

[16] B. R. Munson, F. Y. Donald and H. O. Theodore, Fundamentals of Fluid Mechanics, New York: 3rd Edition, John Wiley and Sons, incorporated, 1998.

[17] W. R. Fox and A. T. McDonald, Introduction to Fluid Mechanics, New York: 8th Edition. John Willey and Sons, Incorporated, 2011.

[18] R. D. Blevins, Applied Fluid Dynamics Handbook, UK: Krieger Publishing Company, 2003.

[19] ASM Handbooks, Volumes 1 and 2, and Engineered Materials Handbooks, Volumes 1 and 4, ASM International, Materials Park, OH; R. F. Floral and S.T. Peters, “Composite Structures and Technologies,” tutorial notes, 1989; & manufacturers’ technical data sheets.

[20] A. Wensley, "Materials for Fabrication and Repair of Batch Digesters," in *NACE Corrosion 98 Conference*, 1997.

[21] A. Wensley, M. Moskal and W. Wilton, "“Materials Selection for Batch Digesters,”," in *NACE Corrosion 97 Conference; Paper No. (378),* 1997.

[22] A. Wensley and H. Dykstra, "Materials for Repair and Protection of Batch Digesters," in *Proceedings NACE Northern Region Western Conference,* Vitoria, British Columbia (BC), 1998.

[23] F. Shi, Reactor and Process Design in Sustainable Energy Technology, 1st Edition, New York: Elsevier Science, 2014.

[24] W. Kossmann, U. Pönitz, S. Habermehl, T. Hoerz, P. Krämer, B. Klingler, C. Kellner, W. Wittur, F. Klopotek and A. Krieg, Biogas Digest, Volume II–Biogas Application and Product Development, vol. II, Eschborn, Germany: Information and Advisory Service on Appropriate Technology (ISAT), 1999.

[25] C. J. Olelewe, E. C. Okoroigwe and D. O. Obikwelu, "Study of the Corrosive Effects of Anaerobic Digestion Slurry on Metal Biodigester by Tafel Polarization Method," in *Proceedings of the 10th Annual and International Conference of the Renewable and Alternative Energy Society of Nigeria held at the*, University of Nigeria Nsukka, Enugu State, Nigeria, 2021.