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Design of Bio-Waste Grinding Machine for Anaerobic Digestion (AD) System

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ABSTRACT

This research work focus on the design of bio-waste grinding machine for Anaerobic Digestion (AD) system. Two different conceptual designs were drawn; the best conceptual design was selected for detail design using decision matrix. The results obtained from the detail design show that a grinding force and power of 150N and 2.5 horse power (HP) were required for grinding an average mass of 5.87 kg of bio-waste. The machine was evaluated for performance and from the analysis, the machine was efficient (71.08%) and it was able to grind the bio-waste to the required sizes. Besides, the fine particles size has shorter hydraulic retention time (HRT) and an improved biogas yields. Therefore, for optimum biogas yields, bio-waste grinding machine is required.

Keywords: Design, Bio-waste, AD system, Grinding machine

INTRODUCTION

Particle sizes are major factor that either reduce or increase hydraulic retention time (HRT) of an Anaerobic digestion (AD) System. Shorter hydraulic retention time brings improves biogas yields [1]. Hydraulic retention time (HRT) is an operation parameter that describes the theoretical period that the sludge stays in the AD plant and the period in which the microorganisms can transform the organic matter into biogas [1-2]. The size of feedstock has direct effects on its decomposition, and this calls for feedstock particles reduction by crushing, grinding, and shredding [3- 4]. Reduction of feedstock sizes lead to an increases surface area for microbes, ultimately improves the efficiency of digester. The most widely used methods of disintegration were mechanical grinding and ultrasound, microwave [5], thermal or their combination and biological pretreatment [6]. The purpose of a grinding and crushing machine is to reduce large solid material objects into a smaller size. Grinders unlike crushers make use of abrasion, often combined with compression to pulverize materials, usually to produce granular products [8]. Crushing is the process of transferring a force amplified by mechanical advantage through a material made of molecules that bond together more strongly, and resist deformation more, than those in the material being crushed do [9-10].

The AD system is a green technology involving the generation of methane rich biogas via the biological degradation of available biomass from bio-waste. It is an efficient process for treatment and utilization of bio-waste because it has proven to be a promising method for waste reduction and energy recycling [11]. The AD system is widely adopted by Germany, Sweden, China, USA, and Denmark, which have implemented rigorous waste disposal legislation. Since 2000, annual power generation from digester projects in USA has increased almost 25- fold from 14 million kilowatt-hours (KWh) to an estimated 331 million kWh per year [12]. Although, several operation and process parameters affect the AD system but the effect of particle sizes must be overcome to ensure shorter hydraulic retention time (HRT) is achieved. So, there is need to reduce the size of bio-waste for easy and fast decomposition, thus, this research work.

BASIC COMPONENT OF THE MACHINE

The machine has the following component:

Main Frame

The main frame was constructed with angle bar. The angle bar is welded together to form the frame work. The welding provides rigid joints and this is in line with modern trend of providing rigid frame as support. This provides strength and rigidity for the machine.

Hopper

The hopper is the receptacle through which bio-waste is admitted into the grinding machine. It has a trapezium plan which tapers gradually.

The Grinding chamber

The grinding chamber consists of the shaft, grinding disc, bearings. The grinding disc is made with mild steel and attached to the solid shaft.

Electric Motor and Pulley System

An electric motor is used to power the machine. A reduction pulley system is used to transmit power to the chamber at reduced speed and increased torque. This enables the shaft and grinding disc to exhibit rotary motion thereby grinding the bio-waste.

Shaft Design

A shaft is a rotating machine element which is used to transmit power from one point to another. The power is transmitted by some tangential force and the resultant torque (or twisting moment) set up within the shafts. In order to transfer the power from the shaft, the various members such as pulleys, bearings etc. are mounted on it. These members along with the force exerted upon it causes the shaft to turn or twist or bend.

Bearings

Ball bearings were used to support the shaft in a relative constraint motion.

DESIGN REQUIREMENT [FUNCTIONAL REQUIREMENT]

The following design requirements were drawn:

- Estimation of force and power required to grind the bio-waste (watts)
- Determination of approximate length of the belt (m)
- Determination of load on shaft pulley and belt tensions (N)
- Determination of driver and driven pulley speed
- Determination of torque transmitted by electric motor
- Determination of bending moment
- Determination of shear force
- Selection of bearing for shaft

Design Consideration

To achieve optimum function for this machine, proper considerations were made to specify and identify some problems which could hinder effective performance and effort was put to identify the factors and constraints as put together.

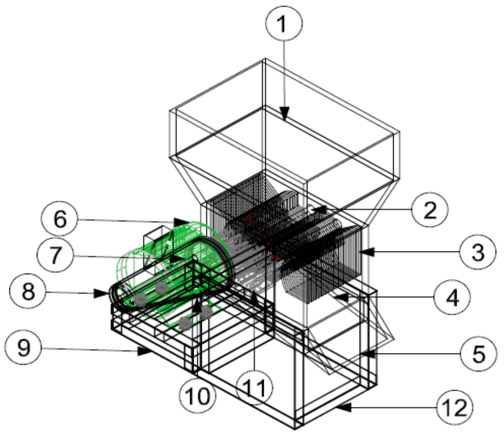
- Functionality
- Reliability
- Durability
- Materials and labor use
- Simplicity
- Portability and space
- Operational procedure
- Power supplier
- Usability
- Maintenance
- Cost
- Safety

Design Concepts

Several design concepts were put forward bearing in mind the design criteria for material selection for various components of the machine which is based on the type of force that will be acting on them, the work they are expected to perform, the environmental condition in which they will function, their useful physical and mechanical properties, the cost, toxicity of materials and their availability in the local market.

Design Concept One

Design concept one (Fig. 1 and 2) makes use of crushing principle and the crushing is done by crushing disc. The discharge end is located at the end of the disc. The crushing discs are fixed to the main shaft and enclosed in the barrel. The machine is powered by an electric motor via belt drive connected to the main shaft that turns the disc crushers. The hopper into which the bio-waste is fed is located at the top of machine. The design of the bio-waste crushing machine includes the determination of the volume of the hopper unit, crushing force and the selection of a convenient material for the construction of the individual units. The bulk of the parts of the machine were fabricated using mild steel, this is because it is the easy to be join among all other metals. It is a versatile metal, necessitating its use by many industries for fabrication or process unit equipment. Apart from its versatility, it is also very cheap and readily available to other metals.



S/NO.	DESCRIPTION
1.	FEED HOPPER
2.	SHAFT
3.	ROTATING CRUSHING BLADE
4.	CRUSHING CHAMBER
5.	CRUSHED PRODUCT OUTLET TRAY
6.	ELECTRIC MOTOR
7.	DRIVEN PULLEY
8.	DRIVE PULLEY
9.	ELECTRIC MOTOR BASE FRAME
10.	DRIVE TRANSMISSION BELT
11.	GEAR
12.	MACHINE FRAME

Fig. 1 Isometric skeletal view of design concept one

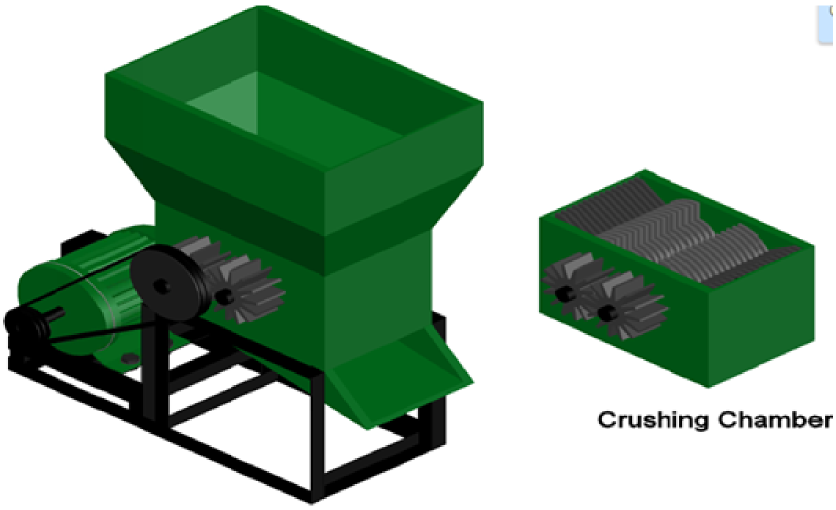
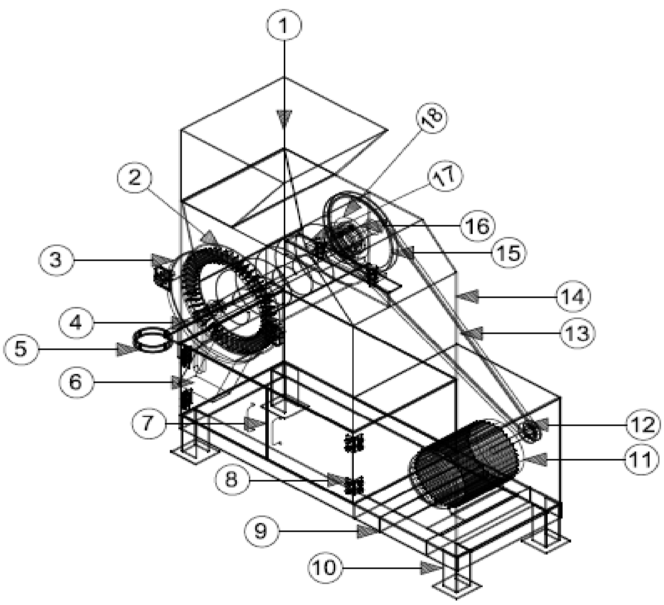


Fig. 2 Model view of design concept one

Design Concept Two

In design concept two, the crushing unit in design concept one was modify (Fig. 3 and 4). The crushing chamber was replaced by grinding chamber to ensure smaller and finer particles size were obtained.



S/NO.	DESCRIPTION
1.	FEED HOPPER
2.	GRINDING DISC TEETHS
3.	GRINDING DISC COMPARTMENT
4.	DISC FIRM ADJUSTER
5.	DISC ADJUSTER BOLT
6.	COLLECTION TRAY
7.	TOOL BOX COMPARTMENT
8.	DOOR HINGES
9.	MACHINE BASE FRAME
10.	MACHINE BASE STAND
11.	ELECTRIC MOTOR
12.	ELECTRIC MOTOR PULLEY
13.	DRIVE BELT
14.	GRINDING CHAMBER
15.	GRINDING SHAFT PULLEY
16.	SHAFT
17.	SCREW CONVEYOR
18.	BALL BEARING

Fig. 3 Isometric skeletal view of design concept two

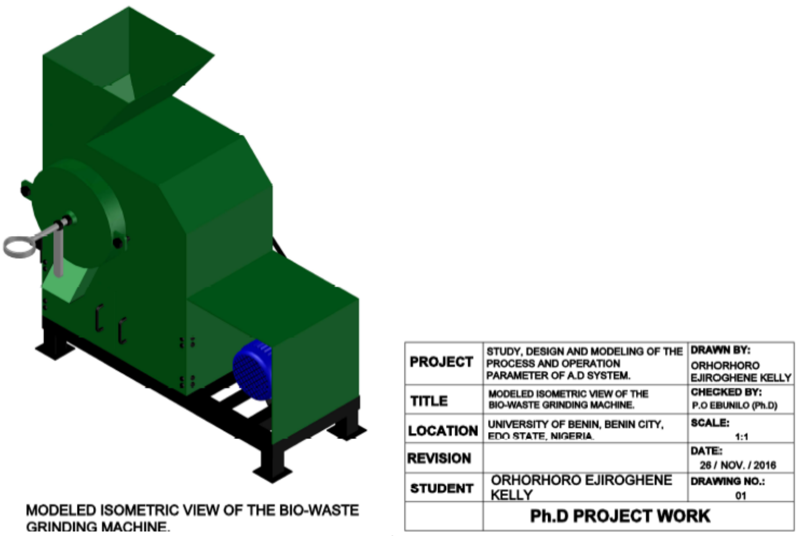


Fig. 4 Model view of design concept two

Table-1 Decision Matrix

Criteria	Weight	Alternatives			
		Design Concept one		Design Concept two	
		Rating	Score	Rating	Score
Functionality	0.30	6	1.8	5	1.5
Performance	0.25	2	0.5	9	2.25
Reliability	0.20	4	0.8	8	1.6
Safety	0.15	2	0.3	9	1.4
Cost	0.10	4	0.4	9	0.9
Total	1.00	18	3.8	40	*7.65

*Weight Factors from 0.10 – 0.30, Rating 1 – 10 and Score 1 – 10. ***Score = Rating x Weight

Based on the ranking, second concept was selected for detail design and fabrication.

Selection of Concept for Detail Design

Decision matrix (Table -1) was used to select the best concept for detail design and fabrication. Decision matrix is a list of values in rows and columns that allow the design engineer to analyze and rate the performance of relationships between sets of values and data. Each category is assigned a weighing factor base on believe which measures its relative importance.

Operation of the machine

Bio-waste is fed into the hopper were it settle at the grinding chamber. The grinding chamber comprise of the shaft embedded with auger and grinding disc. The driver pulley connected to the electric motor shaft drive the shaft in the grinding chamber with the help of V-belt that connect both pulley once the electric motor is switch on. The rotation of the shaft presses the bio-waste against the grinding disc were grinding is done.

Material Selection

The material selection for this work is based on -

Service Requirement

Service requirement in material selection entails the properties a material should have, to serve the purpose for which it is designed for, examples include: hardness, strength, stiffness, toughness, corrosion resistance, resistance to heat, conductivity, etc.

Fabrication Requirement

Fabrication requirement entails workable properties a material should have, and they include machinability, forgability, malleability, ductility, weldability, castability, etc.

Economic Requirement

Economic requirement in material selection entails the affordability of the material for fabrication and commercialization. It would not be profitable to manufacture at a high cost and sell below the manufactured cost.

Choice of Material

The following materials listed in Table -2 were selected for various component parts of the machine.

Table -2 Selected Component Parts of the Machine

S No	Component Description	Material	Justification
1	Metal Sheet	Stainless Steel	*Ability to resist corrosion. *At high temperatures it prevents scale and maintains strength.
2	Angle bar	Mild steel (Low carbon steel)	*Ability to withstand shear force and compressive force
3	Pulley	Cast iron	*Tough, hard, low cost and has high strength
4	Shaft and Crusher blade	Stainless steel	*Ability to resistance corrosion *Ability to withstand shear force and compressive force.
5	Belt fibre	Reinforced rubber	*It is strong, flexible and durable, *It has a high coefficient of friction
6	Flange Ball bearing	High Carbon Steel	*Resistance to wear and corrosion, hard, tough and has high strength.

DESIGN DETAILS

This phase builds on the selected concept, aiming to further elaborate each aspect of the work by complete description through solid modeling, mathematical modeling, working drawing as well as specifications.

Crushing Force

The crushing force is the force requires to crush the PET bottles waste to the desire sizes and is calculated from the equation (1).

$$T=Fr \qquad \text{[Here, T=Torque and F= grinding force]} \qquad (1)$$

Grinding Power

The power requires to crush PET bottles waste is given by (2)

$$P = FV \qquad \text{[Here, P = Power to turn the shaft and V = speed]} \qquad (2)$$

Force (F) = mass (m) x acceleration due to gravity (g) = 145N

But,

$$V = \frac{\pi DN}{60} \qquad (3)$$

Here, V= Speed, D= Diameter = 150mm =0.15m, d = 50mm =0.10m, R =75mm= 0.075m, r = 25mm = 0.025m

N= Speed in revolution per minute = 1440 rpm

From equation (2)

$$P = \frac{F\pi DN}{60} = \frac{150 \times \pi \times 0.15 \times 1440}{60} = 1{,}640 watts$$

But, 1hp = 750 watts

Thus, 1,640watts = 1.64hp

Considering a safety factor of 1.5, Approximately 2.5hp will be required

Belt Design [15]

$$2.3 \log \left({}^{T_1}/_{T_2} \right) = \mu\theta \qquad (4)$$

Here, θ = angle of wrap of an open belt, μ = coefficient of friction, T_1 = Tension in the tight side of the belt T_2 = tension in the slack side of the belt and *x* = distance between the pulleys

For cross belt, Angle of contact is given by -

$$\sin\alpha = \frac{R+r}{x} \qquad (5)$$

For open belt, Angle of contact is given by -

$$\sin\alpha = \frac{R-r}{x} \qquad (6)$$

Angle of wrap -

$$\theta = 180 \pm 2\sin^{-1}\left(\frac{R-r}{x}\right) \qquad (7)$$

Here, r = radius of small pulley, R = radius of big pulley, X = distance between the two pulleys

For peeling machine with inner (rotation) the angle of contact is,

$$\theta = 180 \pm 2\sin^{-1}\left(\frac{R-r}{x}\right) \qquad (8)$$

$$P = (T_1 - T_2)v \quad (9)$$

Here,
P = Belt power (watts), V = Belt speed (m/sec) and T_1 and T_2 are tension on the tight and slack sides respectively
But,

$$T_1 - T_2 = \frac{p}{v} \quad (10)$$

Recalling, $$2.3\log\left(T_1/T_2\right) = \mu\theta$$

Where,
μ= coefficient of friction between belt at pulley for mild steel pulley and rubber belt 0.30 [15].

Design for Velocity Ratio for Belt Drive [13]
Velocity ratio for belt drive is the ratio between the velocity of the driver and the follower (driven). It may be expressed mathematically as:

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \quad (11)$$

Here, d_1 = diameter of the driver, d_2 = diameter of the follower, N_1 = speed of the driver, N_2 = speed of the follower

Length of the belt that passes over the driver in one minute is given by,

$$\pi d_1 N_1 \quad (12)$$

Similarly, length of belt that passes over the follower in one minute is given by,

$$\pi d_2 N_2 \quad (13)$$

Since the belt passes over the driver in one minute and is equal to the length of the belt that passes over the follower in one minute
This implies:

$$\pi d_1 N_1 = \pi d_2 N_2 \quad (14)$$

Therefore,

$$\frac{N_2}{N_1} = d_1/d_2 \quad (15)$$

Design for Shaft [13]

$$T_D = \frac{60PK_l}{2\pi N} \quad (16)$$

T_D= Design torque = Fr
K_l= Load factor=1.75 for line shaft

Thus, for diameter of shaft

$$\tau_{max} = \frac{16}{\pi d^3}\sqrt{(K_b M)^2} + (K_t T_d)^2 \quad (17)$$

Here, M=Bending moment

For suddenly applied load (heavy shock), the following values are recommended for Kb and K_t [15]

K_b= 2 to 3 and K_t= 1.5 to 3

Selecting material of shaft SAE 1030

S_{ut}= 527MPa

S_{yt}=296MPa τmax≤0.30Syt τmax≤0.18Sut

Here, Sut= Ultimate yield strength and S_{yt}= Yield strength

Selection of Bearing

$$L_{10} = \frac{60 \times L \times N}{10^6} \quad (18)$$

Where, L_{10}= basic dynamic life of the bearing (million rev.)

L = Life of the bearing $[L = 18{,}000 \leq 22{,}000]$ and N = 1440rpm
Also,

$$F_e = (xC_r F_r + C_t F_t)S_f \quad (19)$$

Here, F_e = Equivalent dynamic load, x = Rotational factor, C_r = Radial factor, F_r = Radial load, C_t = Thrust factor, F_t = Thrust load, S_f =Safety or service factor and x=1 (inner raceway)

$S_f = 1.1 \leq S_f \leq 1.5$ (for rotating part)

If, $$\frac{f_t}{xFr} \leq 0 \quad (20)$$

$C_r = 1$ and $C_t = 0$

And $$\frac{f_t}{xFr} > 0 \quad (21)$$

C_r=0.56

C_t is interpolated or extrapolated.

Figure 5 shows the detached isometric view of bio-waste grinding machine.

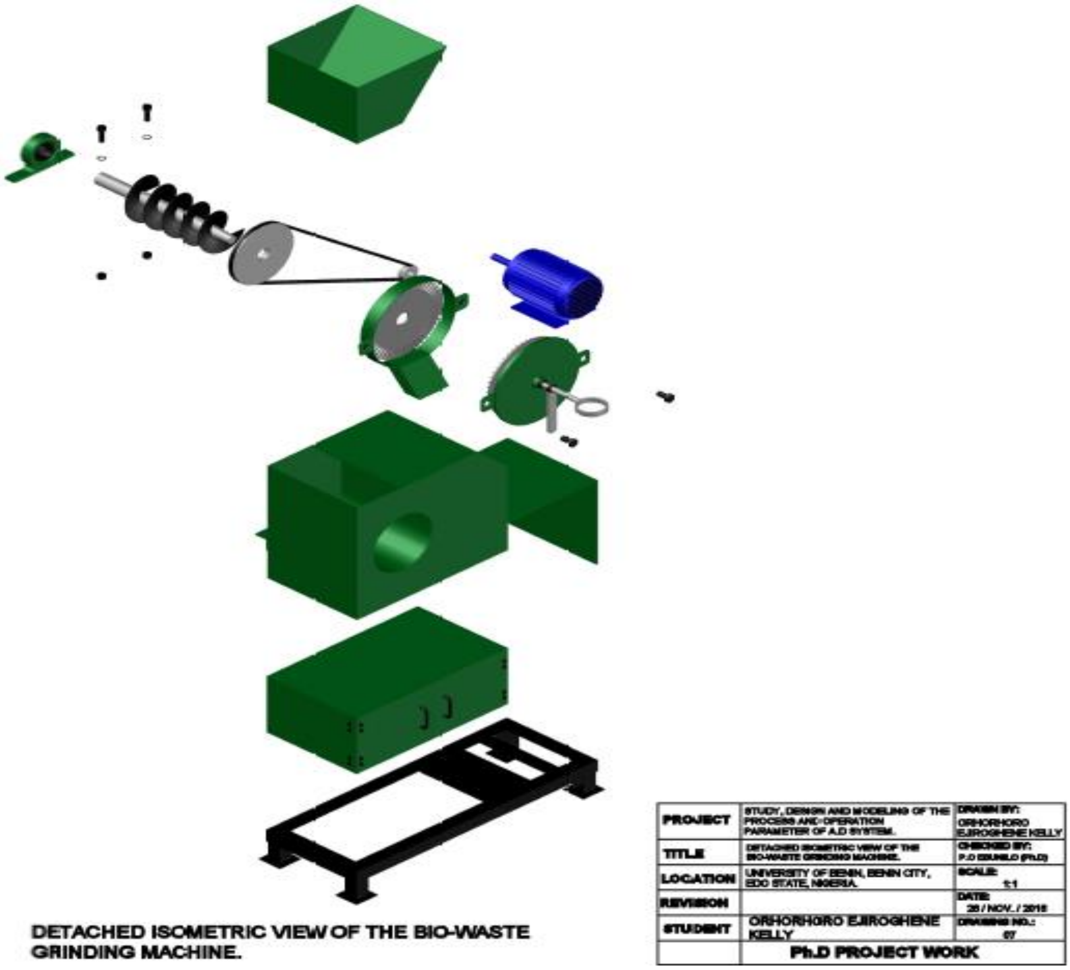


Fig. 5 Detached isometric view

Table-3 MTC and Efficiency

S No	M_1(kg)	M_2 (kg)	T (sec)	MTC (kg/sec)	Efficiency (%)
1	5.45	4.81	98	0.056	88.26
2	4.45	3.81	86	0.052	85.62
3	5.43	4.00	93	0.058	73.66
4	7.01	5.21	101	0.069	74.32
5	4.49	3.27	88	0.051	72.83
6	6.00	4.32	99	0.061	72.00
7	9.51	7.33	121	0.079	77.08
8	6.31	5.11	102	0.062	80.98
10	10.05	8.65	129	0.078	86.07
Σ	58.70	46.51	917	0.566	710.82
Ave.	5.87	4.65	91.70	0.057	71.08

RESULTS AND DISCUSSION

The results obtained with bio-waste grinding machine is shown in Table -3.
M_1 = Mass of biodegradable organic waste and M_2 = Mass of properly grind biodegradable organic waste
The machine through put capacity (MTC) is calculated from equation 22 -

$$MTC = \frac{M_1}{T} \quad (22)$$

Here, T = Machine grinding time
The tests were carried out ten consecutive times. The average mass of ungrounded biodegradable organic waste and grinded biodegradable organic waste were calculated and it was used to determine the efficiency of the designed grinding machine (Equation 23 and 24). The results obtained showed that an average efficiency of 71.08% was obtained.

$$Ave. = \frac{\Sigma}{N} \quad (23)$$

$$Eff. = \frac{Output}{Input} \times 100 = \frac{M2}{M1} \times 100 \quad (24)$$

Fig. 5 present the plot of grinding time, mass of biodegradable waste, machine throughput time and efficiency. Table -4 shows the effect of particle size on hydraulic retention time of anaerobic digestion system. Same quantity (mass)of biodegradable organic waste was used in both sample.
Sample A= Grinded bio-waste (fine particle sizes) and Sample B = Ungrounded bio-waste (Coarse particle size)

The results in Table -4 shows that sample A has shorter hydraulic retention time (HRT). This implies that the smaller the particle size, the faster the rate of decomposition, thus, the short hydraulic retention time (HRT) obtained. Since HRT is a function of optimum biogas yields, the use of fine particle sizes will improve biogas yields.

Table-4 Effect of Particle Sizes on HRT

Sample A		Sample B	
M_A	HRT_A	M_B	HRT_B
7.45	26	7.45	36
6.45	25	6.45	34
7.05	26	7.05	35
5.55	23	5.55	32
6.35	24	6.35	34
10.67	28	10.67	38

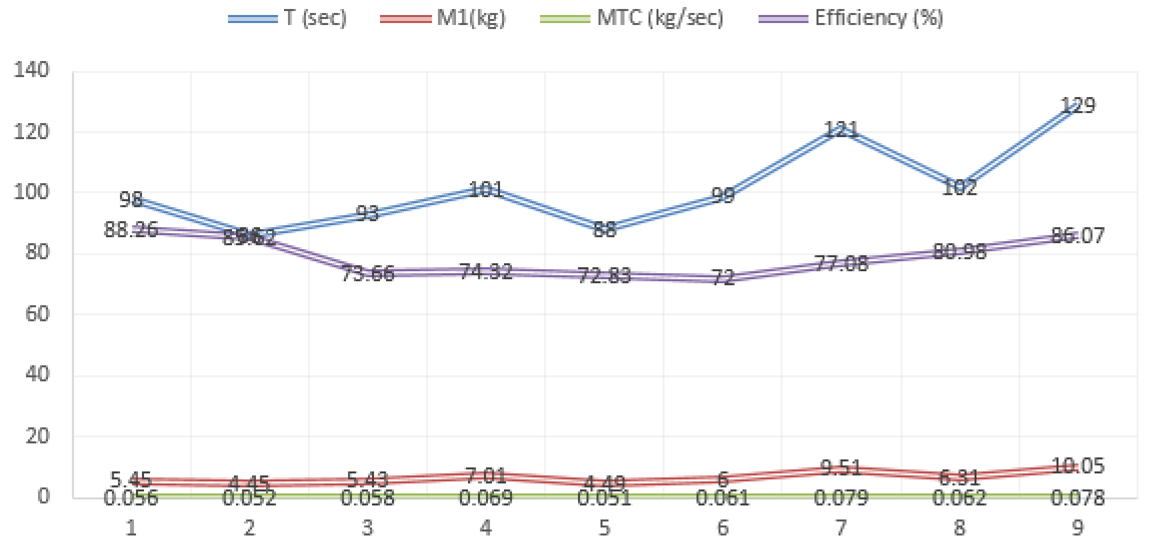


Fig. 5 Plot of grinding time, mass of biodegradable waste, machine throughput time and efficiency

CONCLUSION

In this research work, bio-waste grinding machine was successfully designed. To determine how efficient, the machine might be, performance evaluation was carried out and the results obtained showed that the machine was efficient (71.08%). The grinded bio-waste was evaluated. The outcome show that fine particle sizes have shorter HRT than coarse particle sizes. Therefore, for optimum biogas production, bio-waste grinding machine will be needed for the reduction of bio-waste sizes.

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