Design and Construction of a Plastic Shredder Machine for Recycling and Management of Plastic Wastes

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Abstract—This research work is aimed at solving the problems of plastic wastes management in developing countries. In this study, we designed and constructed a plastic shredding machine. The machine consists of the following main components; hopper assembly, shredding chamber, drive shaft, frame, V-belts, and an electric motor. The machine was evaluated for performance using generated plastic wastes in the environment of Petroleum Training Institute, Effurun, Nigeria. The results obtained show that the machine has a hopper capacity of 0.066m3, centrifugal tension of 9.74N, maximum tension of 229.5N, shredding force of 680.547N, shaft diameter of 29.5mm, bending stress of 86MPa, shearing stress of 42MPa, and torque of 29.21Nm. Also determined was the total force acting on the flywheel which was gotten as 728.367N, equivalent bending moment of 210.35Nm, and forces acting on the pulley as 478.63N. The performance evaluation of the machine gave a result of 98.44% shredding efficiency, a shredding rate of 0.575kg/s. The shredded plastic wastes has a size ranging between 10mm to 20mm.

Index Terms—Solid waste management, plastic waste, shredder machine, development, efficiency, shredding rate

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1 INTRODUCTION

Municipal solid waste (MSW) generation in developing countries is a major concern to government, institution and the society at large; this solid waste is worrisome especially with an increasing population pressure and socio-economic factors in Nigeria [1-2]. Solid wastes are the unusable and undesirable products in solid state, discarded by members of the society [3-4]. Generally, solid wastes can be classified on the basis of their source as: Municipal Solid Waste, Industrial Solid Waste and Agricultural Solid Waste. Most cities in Africa spend 20-50% of their environmental budget on solid waste management and only 20-80% of the waste is collected [5-6]. Furthermore, the standard of solid waste management in Nigeria is at its lowest with poor documentation of waste generation rates, inefficient storage and collection system, and the under-utilization of disposal sites [7]. Nigeria's urban cities are today struggling to clear heaps of solid waste from its environment [5]. Strategic centres of desirability in Nigeria are now taken over by the shambolic nature of unattended tons of solid waste emanating from the society. City officials appear unable to combat unlawful dumping of solid house-hold and industrial waste, which is a clear defilement of the clean Air and Health Edicts in our environmental sanitation laws and regulations in Nigeria [8].

Plastic waste is a constituent of the solid waste stream of which polyethylene terephthalate (PET) is a part. PET is used to produce plastic bottles and several other plastic products [5]. Most bottles produced from PETs are transparent in nature and used for packaging water, soda etc. They are non-biodegradable and can stay unchanged for as long as 4500 years on earth causing menace to our lands, streams and drainage systems [9]. Plastic waste accounts for more than

20% of the municipal solid waste stream in Nigeria [10]. The problem of plastic waste is not only limited to Nigeria rather it is a worldwide phenomenon. The world's annual consumption of plastic materials have increased from around 5 million tons in the 1950's to more than 100 million tons; thus, twenty (20) times more plastic is produced today than in the past fifty (50) years ago [11]. This simply means that more resources are being used to meet the increased demand for plastic, thus, more plastic waste is being generated [11]. The continuous increase in hot weather as a result of global warming coupled with the lack of accessible safe drinking water in both rural and urban areas of Nigeria's growing population drives constant demand for bottled water [12]. Although some areas do have public water systems available but distribution channels are not trusted to provide safe drinking water. Many Nigerians own private boreholes but the purification system is often poor.

According to NAFDAC director-general Dr. Paul Orhii, Nigeria with an estimated population of one hundred and sixty seven million (167,000,000) people, one hundred million (100,000,000) take bottled water daily [13], thus generating one hundred million (100,000,000) wastes of PET bottles. PET bottle wastes are generated from environments where people inhabit like hotels, restaurants, offices, schools, markets, motor parks, hospitals, events etc. [5]. It is observed in Nigeria that most PET bottles produced are not retrieved and recycled by the plastic producers. But, new bottles are produced daily, thus, increasing the litter in the country without alleviating the menace posed by it. The limited or absence of recycling machines and probably ignorance of recycling technologies in the country has led to the non-recycling of littered waste PET bot-

tles, as compared to other countries in the world. In 2011, 59.6% of plastics were recovered and recycled in Europe (EU-27), while in 2012 this increased to 61.9% [14]. In this line, we decided to designed and construct a plastic shredding machine for plastic wastes management in Nigeria.

A shredding machine is designed to reduce large solid material objects into a smaller volume, or smaller pieces. Shredding machines are usually used to reduce the size and shape of materials so they can be efficiently used for the purpose intended to. Shredding just like crushing can be defined as 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 [15]. The shredding materials must possess a better strength and toughness than the plastic materials.

2   MATERIALS AND METHOD

The plastic shredding machine is made up of several parts which are listed below:

2.1 Hopper

The hopper is made from mild steel of thick sheet metal plate (0.22 mm). It is the unit which receive and accumulate waste plastics while shredding is in progress. The upper part is framed with angle bar (0.33mm) for rigidity. It is the unit where plastics are feed to the shredding chamber. It has a truncated cone shape.

2.1 Shredding Chamber

The shredding chamber is made with thick rigid mild steel (0.610mm) plate. All the joint parts were welded with arc welding except the side which is bolted for purpose of easy coupling and uncoupling. A smaller plate of (0.03mm) plate is used to cover the front side of the shredding chamber. This fixture is created for easy maintenance of the shredding blades and the housing. It is equally constructed in such a way that stuck plastics wastes are easily removed. A mesh is attached to the bottom of the shredding chamber to regulate the size of successfully shredded plastic pieces.

2.3 Mesh

At the base of the shredder housing is the mesh. It is made of steel wire. It is used to regulate the type and size of the shredded plastic wastes. It is only the sizeable plastic that have been reduced to smaller sizes passed through the mesh while the bigger sizes roll back for more proper shredding.

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2.4 Gusset Channel

2.5 Main Frame

The main frame is constructed using angle bar of 0.3mm x 40mm x 40mm. It is made of mild steel. The angle bar was cut to size and welded together to produce the skeletal frame.

2.6 Fly Wheel

A flywheel is a heavy material attached to a drive shaft having most of its weight concentrated at the circumference. The wheel resists changes in speed and helps steady the rotation of the shaft and equally uneven torque on the shaft or where the load is intermittent.

2.7 Cover Plate

At the top of the cutting chamber is the welded steel plate. It covers one-third of the entire top.

2.8 Detail Designed

2.8.1 Estimation of Total Power Requirement

The weight of plastic material required to fill up the machine hopper chamber is given by;

$$W_p = V_h \rho_p g \tag{1}$$

Where,

W_p =weight of the plastic material in N

V_h =Volume of the machine hopper unit

$\rho_p = Bulk\ density\ of\ plastic\ material$

2.8.2 Volume of hopper

The required volume is the volume of bigger pyramid minus volume of smaller pyramid

$$V_h = \frac{LWH}{3} - \frac{lwh}{3} \tag{2}$$

where,

L and l = Base length of bigger and smaller pyramid respectively

W and w= Base width of bigger and smaller pyramid respectively

H and h= Height of bigger and smaller pyramid respectively

By principal of similar triangles

Hence, the volume of the hopper is;

$$V_h = \frac{0.54 \times 0.54 \times 0.78}{3} - \frac{0.27 \times 0.27 \times 0.39}{3} = 0.066 m^3$$

But, weight of the plastic material required tofill up the machine hopper;

$$W_p = V_H \times \rho_p \times g$$

But, density polyethylene = 970kg/m³

$$W_p = 0.066 \times 970 \times 9.81 = 628.036N$$

2.8.3 Design and Analysis of Belt Drive
Length of V-belt

$$L = \pi (r_2 + r_1) + 2x + \frac{(r_2 - r_1)^2}{x} \tag{3}$$

where,
r_1 and r_2 = Radii of the larger and smaller pulleys
x = Distance between the centres of two pulleys
r_1 = 0.065m
r_2 = 0.080m
x = 0.028m

$$L = \pi(0.08 + 0.065) + 2(0.028) + \frac{(0.08 - 0.065)}{0.028}$$

L = 1.0m

2.8.4 Angle of lap on the smaller pulley

$$\theta = 180° - 2\left[\sin^{-1}\left(\frac{d_2 - d_1}{2x}\right)\right] \tag{4}$$

where,
d_2 = diameter of the driven pulley
d_1 = diameter of driver pulley

2.8.5 Ratio of Driving Tensions for V-belt

$$2.3\log\left(\frac{T_1}{T_2}\right) = \mu \cdot \theta \cos ec\beta \tag{5}$$

where,
T_1 = Tension on tight side of the v-belt
T_2 = Tension on slack side of the v-belt
μ = Coefficient of friction between the belt and sides of the groove
Θ = Angle of lap on the smaller pulley (pulley on the motor shaft)

2.8.6 Velocity Ratio of Belt Drive

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \tag{6}$$

where
d_1 = Diameter of the driver
d_2 = Diameter of the follower
N_1 = Speed of the driver in rpm
N_2 = Speed of the follower in rpm

2.8.7 Mass of the Belt per Metre Length

$$M = Area \times Length \times Density \tag{7}$$

2.8.8 Velocity of the Belt (V)

$$v = \frac{\pi d_1 N_1}{60} \tag{8}$$

where,
d_1 = Diameter of the driver
N_1 = Speed of the driver in rpm

2.8.9 Centrifugal Tension (T_c)

$$T_C = m \cdot v^2 \tag{9}$$

m = Mass of belt per metre length
V = Velocity of V-belt

2.8.10 Maximum Tension (T)

$$T = \sigma \times a \tag{10}$$

where;
σ = Permissible tensile stress of belt material
a = Cross-sectional of belt material

2.8.11 Tension in Tight Side (T_1)

$$T_1 = T - T_C \tag{11}$$

where,
T = Maximum tension
T_C = Centrifugal tension

2.8.12 Tension in Slack Side (T_2)

$$2.3\log\left(\frac{T_1}{T_2}\right) = \mu \cdot \theta \cos ec\beta \tag{12}$$

where,
T1 = Tension in tight side of pulley
μ = Coefficient of friction between belt and pulley material
Θ = Angle of lap in radians
β = Half of the pulley groove angle in degree

2.8.13 Power Transmitted Per V-belt (P)

$$P = (T_1 - T_2)v \tag{13}$$

where,
T_1 = Tension in tight side of v-belt
T_2 = Tension in slack side of v-belt
V = Velocity of v-belt

2.8.14 Design of the Shaft
Total force acting on pulley is given by Equation (14)
$$F_P = W_p + 2T_1 + 2T_2 \tag{14}$$
Where;
W_P = Weight of pulley
T_1 and T_2 = Tension in the tight and slack side of the belt respectively
The force acting on Flywheel is given by Equation (15)
$$F_F = W_F + F_{FT} \tag{15}$$
W_F = Weight of flywheel
F_{FT} = Tangential force due to torque transmitted by shaft
The force acting on the shredding drum is given by Equation (16)
$$F_C = W_C + F_{CT} \tag{16}$$
where,
W_C = Weight of flywheel
F_{CT} = Tangential force due to torque transmitted by shaft

2.8.15 Diameter of the Shaft
Using equivalent twisting moment:
$$T_e = \sqrt{(K_m \times M_B)^2 + (K_t + T)^2} = \frac{\pi}{16} \times \tau \times d^3 \tag{17}$$

Using equivalent bending moment

$$M_e = \frac{1}{2}\left[K_m \times M + \sqrt{(K_m \times M_B)^2 + (K_t + T)^2} \right] = \frac{1}{2}\left[K_m \times M + T \right]$$
(18)

where,
K_m = Combined shock and fatigue factor for bending
Kt = Combine shock and fatigue factors for twisting or torsion
M = Bending moment
Te = Equivalent twisting moment
τ = Shear stress induced due to twisting moment
σ_b = Bending stress induced due to bending moment
d = Diameter of the shaft
The diameter of the shaft is obtained by using both the theories and the larger of the two values is adopted.

The length of key considering shearing of the key is given by Equation (19)

$$l = \frac{2T}{w \times d \times \tau}$$
(19)

where,
 = Length of key
T = Torque transmitted by the shaft
d = Diameter of shaft
w = Width of key
t = Thickness of key
τ = Shear and crushing stresses for the material of key

However, the length of key considering crushing of the key is given by Equation (20)

$$l = \frac{4T}{t \times d \times \sigma_C}$$
(20)

l = Length of key
T = Torque transmitted by the shaft
t = Thickness of key
d = Diameter of shaft
σ_c = Crushing stresses for the material of key

2.8.16 Torque Transmitted by Shaft

$$T = \frac{P \times 60 \times 1000}{2 \times \pi \times N} \text{ KW}$$
(21)

where,
P = Power transmitted by electric motor
N_2 = Revolution of the shaft in rpm

The main loads on the shaft are the bearing reactions, the weights of the pulley, flywheel, cutting drum and belt tensions. The shaft will be subjected to fluctuating torque and bending moments, and therefore combined shock and fatigue factors are taken into account.
Since the feeding of the plastic material is gradual and steady, thus;
K_m = 1.5, and
K_t = 1.0
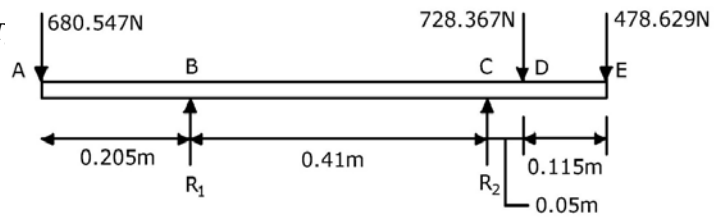The loading diagram is shown below

Fig.1 Forces acting on Shafts

Taking moment about R_1
$$R_2 \times 0.41 + 680.547(0.205) = 728.367 \times 0.46 + 478.629 \times 0.575$$

$$0.41R_2 + 139.512 = 335 + 275.212$$
$$R_2 = \frac{470.7}{0.41} = 1148 \text{ N}$$
Assumption;
Sum of forces acting upwards = sum of forces acting downwards
$$R_1 + R_2 = 680.547 + 728.367 + 478.629$$
$$R_1 + R_2 = 1887.543 \text{ N}$$
$$\Rightarrow R_1 = 1887.543 - 1148 = 739.543 \text{ N}$$

2.8.17 Shear Force and Bending Moment Calculation
Shear Force:
Between A and B,
SF = -680.547N
Between B and C,
SF = -680.547 + 739.543 = 58.996N
Between C and D,
SF = -680.547 + 739.543 + 1148 = 1207.543n
Between D and E,
SF = -680.547 + 739.543 + 1148- 728.367 = 479N
Thus, Bending Moment;
Bending moment at A,
M_A = 0
Bending moment at B;
M_B = 680.544 x 0.205 = 139.512Nm
Bending moment at C;
M_C = -(680.544 x 0.615) + (739.543 x 0.41) = -115.322 Nm
Bending moment at D;
M_D = - (680.547 x 0.665) + (739.543 x 0.46) + (1148 x 0.05) = -55Nm
Bending moment at E;
M_E = - (680.547 X0.78) + (739.543 X 0.575) + (1148 X 0.165) – (728.365 X 0.115) = 0

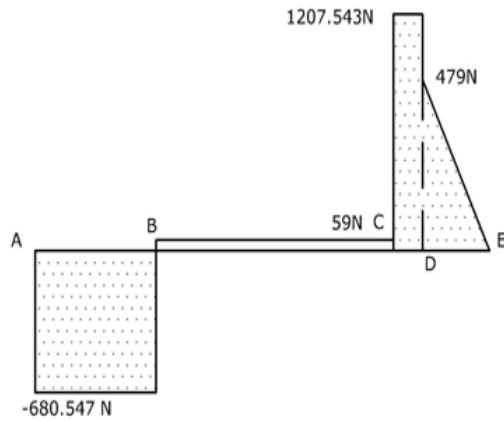Fig. 2 Shear Force Diagram

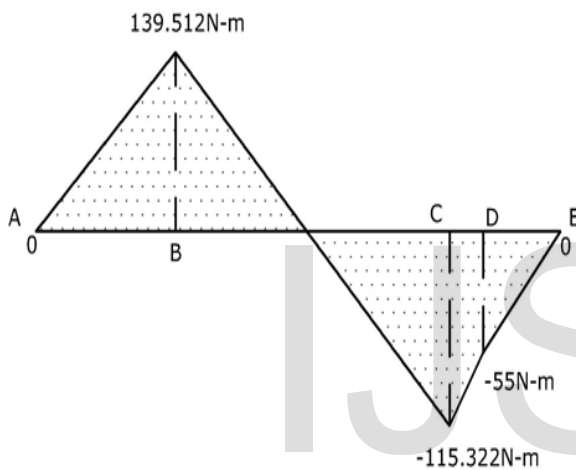Fig.3 Bending Moment Diagram

Therefore maximum bending moment occurs at B,

$M_{max} = M_B = 139.512Nm$

Maximum bending moment,

3 RESULTS AND DISCUSSION

The dimensioned view, isometric view, exploded view, and fabricated shredding machine is shown in Fig.4-Fig.8. The fabricated machine was evaluated for performance using plastic wastes. Table 1 shows the result of the results obtained. Three tests were carried out consecutively, different quantities of plastics wastes were collected, weighed and the average recorded (25.2kg). In each of the test, the time taken to shred the plastic wastes were recorded, and the average gotten as (43.8sec). The average weight of the properly shredded plastic wastes was the average of test 1, test 2, and test 3, and was gotten as 24.66kg. These average weights together with the average weight of collected plastic wastes were used to calculate the efficiency of the plastic shredder machine which was gotten as 98.44%. Thus, the machine performance was satisfactory and it was able to properly shred plastic generated plastic wastes. Furthermore, the shedding rate of the machine was obtained as 0.575kg/s. This once shown again that the ma-

chine throughput capacity is satisfactory.

$$Shredding\ Rate = \frac{Average\ weight}{Average\ time}$$
$$= \frac{25.20\ kg}{43.8\ s} = 0.575 kg/s$$

$$Shredding\ Efficiency = \frac{Mean\ weight\ of\ shredded\ plastic\ wastes}{Mean\ weight\ of\ plastic\ wastes}$$
$$= \frac{24.66}{25.05} \times 100 = (0.9844 \times 100)$$
$$= 98.44\%$$

Table 2 shows the results of detail designed. The results revealed that the machine has a hopper capacity of 0.066m3, centrifugal tension of 9.74N, maximum tension of 229.5N, shredding force of 680.547N, shaft diameter of 29.5mm, bending stress of 86MPa, shearing stress of 42MPa, and torque of 29.21Nm. Also determined was the total force acting on the flywheel which was gotten as 728.367N, equivalent bending moment of 210.35Nm, and forces acting on the pulley as 478.63N.
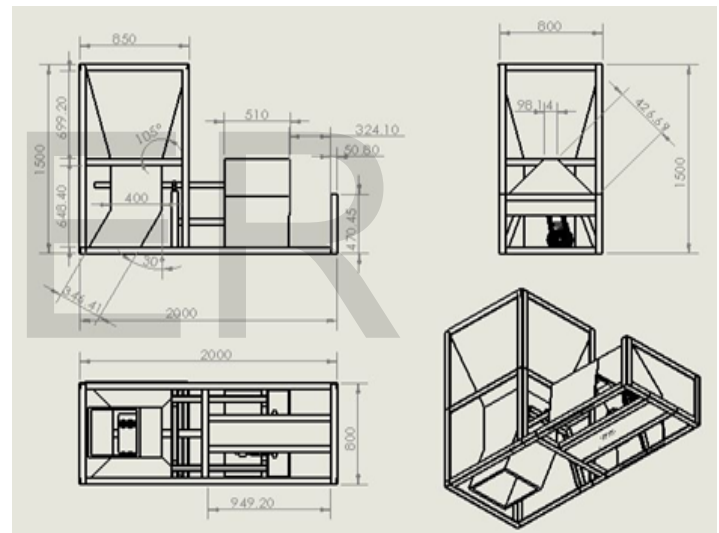

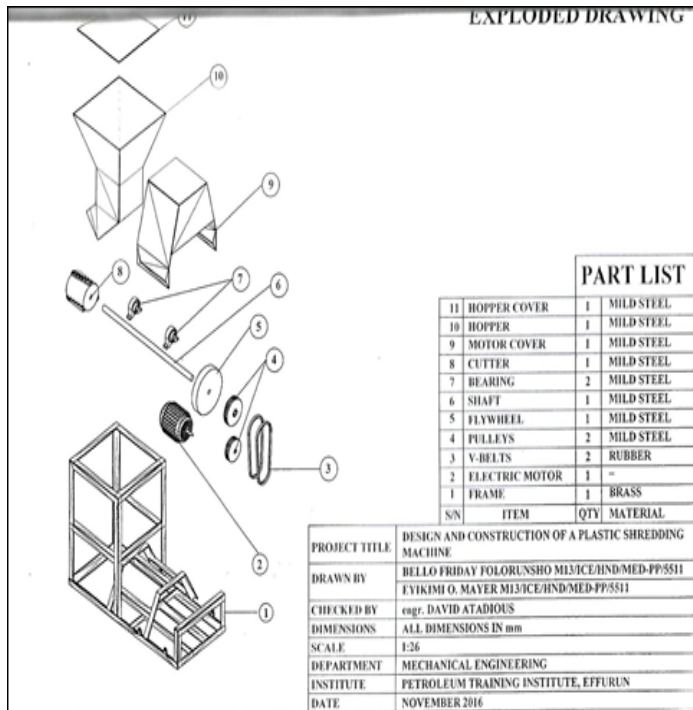Fig. 4 Dimensioned Views

Fig. 5 Isometric view

Fig. 6 Exploded view

Fig. 7 Fabricated plastic shredding machine

Table-1 Performance test results

Reading	Test 1	Test 2	Test 3	Average
Mean weight of plastic wastes (kg)	25.05	25.05	25.5	25.2
Average shredding time (sec)	37.2	45	49.2	43.8
Mean weight of shredded plastic wastes	24.69	24.65	24.63	24.66

Table-2 Detail designed results

Volume of hopper	0.066m³
Density of plastics	970kg/m³
Weight of plastics	628.03N
Length of belt	1.0m
Angle of lap on the smaller pulley	3.13rad
Velocity ratio of belt drive	1
Mass of belt per metre length	0.0934kg/m
Velocity of belt	10.21m/sec
Centrifugal tension	9.74N
Maximum tension	229.5N
Tension in tight side	219.76N
Tension in slack side	12.24N
Power transmitted per V-belt	5hp
Number of V-belts	2
Torque	29.21Nm
Forces acting on the pulley	478.63N
Total forces acting on the flywheel	728.367N
Shredding force	680.547N
Shaft diameter	29.5mm
Equivalent bending moment	210.35Nm
Bending stress	86MPa
Shearing stress	42Mpa

4 CONCLUSION

A plastic shredding machine was designed and successfully constructed. This was aimed at solving the problems of indiscriminate dumping of plastic solid wastes. The machine was evaluated for performance. Collected plastics wastes were shredded with the machine and the results obtained reveal that the machine performance is satisfactory.This machine when commercialized will meet the demand for plastic wastes management.

REFERENCES

[1] F.K. Omole, and M..K. Alakinde, "Managing the Unwanted Materials: The Agony of Solid Waste Management in Ibadan Metropolis", Nigeria, *International Journal of Education and Research,* 2013, 1(4),1-9

[2] E.K. Orhorhoro, P.O. Ebunilo, E.G. Sadjere, "Determination and Quantification of Household Solid Waste Generation for Planning Suitable Sustainable Waste Management in Nigeria", *International Journal of Emerging Engineering Research and Technology,* 2017,5(8),1-9

[3] D.J. Hurd, "Best Practices and Industry Standards in PET Plastics Recycling, Washington State Department of Community", Trade and Economic development's clean Washington center. New York: Bronx 2000 Associates, Inc. 1809 Carter Avenue Bronx, Ny 10457, **1995**,1-4

[4] E.K. Orhorhoro, A.E. Ikpe and R.I. Tamuno, "Performance Analysis of Locally

Design Plastic Crushing Machine for Domestic and Industrial Use in Nigeria", *European Journal of Engineering Research and Science,* 1(2), 26-30

[5] S.N; Momodu, K.O. Dimuna, and J.E. Dimuna, "Mitigating the impact of Solid Wastes in Urban Centres in Nigeria". *Journal of Human Ecology,* **2015,** 34(2), 125-133

[6] E. Achankeng, Globalization, "Urbanization and Municipal Solid Waste Management in Africa", *African Studies Association of Australasia and the Pacific Conference Proceedings - African on a Global Stage, University of Adelaide,* **2003**

[7] A.A. Kadafa, A. Adati, A.B.D. Latifah, A.H. Sulaiman, and W.N. Azmin, "A Review on Municipal Solid Waste Management in Nigeria", *Journal of American Science,* **2012,** 8(12), 975-982

[8] I.H. Owamah, O.C. Izinyon, P. Igbinewekan, Characteristics and quantification of solid waste generation in the Niger Delta Region of Nigeria: a case study of Ogbe-Ijoih community in Delta State, "*Journal of Material Cycles and Waste Management*", 2015, 19(1), 366-373

[9] G. Ionescu, E.C. Rada, M. Ragazzi, C. Marculescu, A. Badea, T. Apostol, Integrated municipal solid waste model using advanced pretreatment and waste to energy processes, "*Energ. Convers. Manag*", 2013, 76, 1083–1092

[10] D. Hoornweg, P. Bhada-Tata, K. Chris, "Environment Waste production must peak this century, Internal weekly journal of science," 2013, 502(7473), 615–617

[11] United Nations Environment Programme (UNEP), Converting Waste Plastic into a resource, United Nations Environmental Programme Division of Technology, "*Industry and Economics International Environmental Technology Centre, Osaka/Shika.*", 2009, 10, 12-73

[12] Euromonitor International, Country report: Bottled Water in Nigeria, 2015, 23-24, Available from: http://www.euromonitor.com/bottled-water-in-nigeria/report

[13] P. Obuh, and N. Uzor, Daily water consumption in Nigeria hits ₦8bn, Vanguard. [Online] 27th October. Available from: http://www.vanguardngr.com/2013/10/daily-waterconsumption-nigeria-hits-n8bn, 2013

[14] Plastics Europe, An Analysis of European latest Plastics Production, Demand and Waste Data, 2013, 24-25. http://www.plasticseurope.org/documents/document/20131014095824-final_plastics_the_facts_2013 _published_october2013.pdf

[15] R.W. Clark. Works of Man: "*History of Invention and Engineering, From the Pyramids to the Space Shuttle*". 1st American Edition. 8"x10" Hard cover ed., Viking Penguin, Inc., New York, NY, U.S.A., (1985). pp. 352, ISBN 9780670804832