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ORIGINAL RESEARCH ARTICLE

DESIGN AND CONSTRUCTION OF AN AGRICULTURAL WASTE-SHREDDING MACHINE

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ABSTRACT

Waste generation has become a major concern to the government, environmental regulatory bodies, and the society, especially with the current population pressure as well as the economic and social factors in Nigeria. This study was focused on design, construction, and performance evaluation of an Agricultural Waste-Shredder using locally available materials. The selected materials used to fabricate the machine were Metal sheet, Angle iron bars, Pulleys, belt, shaft, and Prime mover. The shredder has the feeding unit, the shredding unit, power transmission unit and the machine frame. The performance of the machine evaluated with beans stalk, the performance indices investigated were shredding efficiency and throughput capacity. Response surface methodology (RSM) was used to Maximize the efficiency of the machine at operational Speeds of 360rpm, 650rpm, and 975rpm with sieve apertures of 20mm, 30mm, and 40mm respectively. Maximum shredding efficiency of 93% was obtained when the shred aperture was 20mm at shredding speed of 975rpm. The maximum throughput capacity was 6.10kg kg/m at speed 975rpm and a minimum value of 5.14kg/m at 325rpm respectively. A quadratic model for shredding efficiency explained 94.78% of the variation in shredding efficiency. R^2 (pred) of 70.42% suggests that the model is fit. The machine is easy to use and with a low cost of production to small and medium scale entrepreneurs in agriculture.

1.0 Introduction

Agricultural waste is defined as the residues from the growing and processing of raw agricultural products such as fruits, vegetables, meat, poultry, dairy products, and crops. They are the non-product outputs of production and processing of agricultural products that may contain material that can benefit man. The economic values are less than the cost of collection transportation, and processing for beneficial use. Their composition will depend on the system and type of agricultural activities and they can be in the form of liquids, slurries, or solids (Obi et al., 2016). The waste generated is dependent on the type of agricultural activities carried out. Agriculture is considered as the major occupation in many parts of the world and producing a range of waste materials requiring a variety of treatment technologies and management practices. The major occupation of the Nigerian population is dependent on Agriculture at subsistence level with their holdings small and scattered. A large part of this population is faced with the problem of managing waste materials before and after harvest (Adewumi and Omoresho, 2002).

Considering the diverseness of crops cultivated in Nigeria by farmers, after harvesting these crops the waste/residues are either burnt or thrown as waste without taking into consideration their nutritive value or lack of waste processing machines available for utilizing the waste.

With the increase in the population, our aim is not only to stabilize agriculture production but also to increase it further in a sustainable manner. Excessive use of agrochemicals like pesticides and fertilizers over the years may affect soil health and lead to declining crop yields and the quality of the products. Hence, a natural balance needs to be maintained at all costs for the existence of life and property. The obvious choice would be judicious use of agro-chemicals and more and more use of naturally occurring materials in farming systems. Hence, the shredder machine is used for shredding. The use of a shredding machine is simply converting macro agriculture waste and food waste into small easily decomposable forms, which can be used as organic manure. The small size of waste will decompose faster than the large or macro size waste. This decomposed waste can be used by the crops and can leads to improvement in soil nutrients and increase the growth and quality of the crops and also improve the soil chemical properties such as supply and retention of soil nutrients, and promotes chemical reactions.

Agricultural waste is comprised of animal waste (manure, animal carcasses), food processing waste (only 20% of maize is canned and 80% is waste), crop waste (corn stalks, sugarcane bagasse, drops and culls from fruits and vegetables, pruning) and hazardous and toxic agricultural waste (pesticides, insecticides, and herbicides, etc.) (Vitali et al., 2013). Expanding agricultural production has naturally resulted in increased quantities of livestock waste, agricultural crop residues, and agro-industrial by-products.

There is likely to be a significant increase in agricultural wastes globally if developing countries continue to intensify farming systems. It was estimated that about 998 million tons of agricultural waste are produced yearly (Agamuthu, 2009). Organic wastes can amount up to 80 percent of the total solid wastes generated in any farm (Brown and Root, 1997). The use of multipurpose agricultural solid waste shredder is believed to be an efficient answer for converting the agricultural production waste materials into valuable material for important use like raw materials and can serve as manure for soil preservation. No matter the size, shape, or color of food processing waste ranging from corn stalks, sugarcane bagasse, drops and culls from fruits and vegetables, and crop pruning size, that are available. The use of a high multipurpose shredder holds the ability to transform every part of the waste into a useful product as the machine can be used again after the appropriate processes of manufacturing, making the processed waste an extremely useful product.

The objective of this study is to develop an Agricultural multipurpose waste-shredding machine to utilize wastes for some economic benefits, this machine will utilize all kinds of agricultural wastes after shredding, and the machine will be economical and practicable. The machine will also reduce the time consuming during the work of chopping or thrashing the crop residues by hand and make availability of the machine at a low cost to make it affordable to the farmers.

2.0 Materials and Methods

2.1 Materials

All the materials for the fabrication of Waste-Shredding machine were sourced locally. Materials used in the construction of the Shredding Machine incudes: The materials used in the fabrication and performance evaluation of the Shredding machine include sheet metal, Angle Iron, Prime mover Shaft, Transmission Belt, Pullies, shredding fingers, bearings, Hitches, Bolts and nuts. Instrumentations used were stopwatch, and digital weighing balance.

2.2 Methods

The Shredding machine was designed and fabricated at the Department of Agricultural and Bio-Engineering Engineering, Adamawa State Polytechnic, Yola, Nigeria. The Machine consists of following major component: Cutting blade, machine frame, sieves, hopper, waste collector, cover, and Belt cover. The procedures for the design, fabrication and performance evaluation including cost implication of the Waste Shredding machine are as follows.

2.2.1 Design Considerations

Mechanical Factors, Operational Factors, and Economic Factors were considered for the successful design, fabrication, and operation of the machine.

The mechanical factors considered were strength, rigidity, and simplicity of materials for the construction of the machine. Accommodate the Average speed of operation to minimize Noise and Vibration. Hopper should accommodate different sizes of agricultural waste available locally. Shredding plate is resistant to rusting for Animal feed hygiene purposes. Shredder holes will be such as to produce the desired size of shredded waste material. Waste collector to collect shredded waste

The Operational Factors considered were Uniformity of shreds produced. High operational speed to achieve fast processing of the materials required to shred. Easy to operate and maintain. High level of operational safety.

The economic factors considered in the development of the Agricultural waste shredder were availability of local raw material for fabrication. Low cost of fabrication. Low cost maintenance.

2.2.2 Design Calculations

2.2.1.1 Determination of Power Requirement

The power requirement of the Sheller was considered one of the important factors considered in the design of the operation of the machine, according to (Shigley, 1986).

$$P = F \times V \tag{1}$$

where:

$P = \text{power } (Nms^{-1})$

$F = \text{Force of shredding } (N)$

$V = \text{Velocity } (ms^{-1})$

The force required for shredding is given as;

$F = m\omega^2 r$

$F = \text{force required to shred waste material}$

$m = \text{mass of shredding blades,}$

$\omega = \text{angular velocity of shaft.}$

$\omega = \frac{2\pi N}{60},$

N speed of shredding (rev/m).

The power delivered by the shaft is given by

$$P = F\omega r \tag{2}$$

2.2.1.2 Determination of Bolt for the Frame

The shear stress was put into consideration to determine the bolts used on the machine. According to (Shigley and Mischke, 2005).

$$S_e = \frac{F_{max}}{\pi d^2/4} \tag{3}$$

where: S_e = allowable endurance stress of mild steel $= 107.969 \times 10^3 KN/m$

$F_{max} = F_{min} + \text{weight of cassava filling the hopper}$

$Fmin = \text{force due to total weight of the machine without load} = 0.8KN$

$$d = \sqrt{\frac{4F_{max}}{\pi S_e}} \quad (4)$$

$d = 0.003m = 3mm$. 4mm bolts were selected for fastening the machine to the frames. After the design, fabrication of the shredding machine was carried out, with strict adherence to design values.

2.2.1.2 Determination of V – Belt Length

To determine the length of the belt used to operate the shredder was based on (Khurmi and Gupta, 2006), the expression for the V-belt length is given as;

$$L = \frac{\pi}{2}(D_s + D_m) + 2C + \frac{(D_s+D_m)^2}{4c} \quad (5)$$

$L =$ Belt Length
$C =$ Center length between two pulleys
$D_s =$ Pitch diameter of the first pulley
$D_m =$ Pitch diameter of the first pulley
The length of the v-belt pulley was determined to be 190cm

2.2.1.3 Determination of Volume of shredder Hopper

The volume of the shredder hopper, V_{sh}, through which the waste materials to be shredded are fed is obtained from equation
The volume of the shortened rectangular based pyramid is given as

$$V_{sh} = \frac{1}{3}(BH - bh) \quad (6)$$

where:
B = The area of the rectangular base for the big pyramid,
H = The height of the big pyramid,
b = the area of the rectangular base for the small truncated pyramid, and
h = the height of the small truncated pyramid.

Parallelogram prism is given as;
$$V = Bh \quad (7)$$
where:
B is the area of the base shape

2.2.1.4 Determination of diameter and speed of Shaft

To estimate the diameter of the shafts used in the machine, the Maximum Shear Stress Theory was applied. This theory according to Khurmi and Gupta, (2005) is appropriate for shafts subjected to combined bending and twisting moments, as it is the case with the shafts in this machine. It is also suitable for mild steel shafts, (which are ductile materials). The shafts used in the machine are made of mild tough steel. The diameter of the shaft was determined using the maximum stress theory (Hall et al., 1980).

$$d = \left[\frac{16}{\pi s}\left(\sqrt{(K_b M_b)^2} + (K_t M_t)^2\right)\right]^{\frac{1}{3}} \quad (8)$$

where: M_b = maximum bending moment on shaft (1000Nmm
M_t= maximum torsional moment on shaft (16540 Nmm)
s = allowable shear stress for steel (310 N/mm^2)
K_t,K_b= fatigue and shock factor for torsion and bending moments (1.5 and 1.0).

One main shaft and three mini shafts attached to the main shafts are involved in the development of the machine. The shafts diameters obtained for the shaft based on the equation above are 26 mm for smaller attached shaft, 75 mm for the main driven shaft. The shredder shaft is rotating within the shredder chamber and it is equipped with knife-edged. These knife-edge sharp edges welded on the shaft allow shredding of the waste materials to be possible as it rotates in the chamber. The shredder shaft speed, V_{SS}, is obtained from equation (2) as in (Khurmi and Gupta, 2005)

$$V_{ss} = \omega_{ss} r_{ss} = \frac{2\pi N_{ss}}{60} r_{ss} \tag{9}$$

where:
ω_{ss} =The angular velocity of the shredder shaft pulley.
r_{ss} = The radius of the shredder shaft pulley.
N_{SS} = The speed in revolutions per minute of the shredder shaft pulley.

2.2.1.4 *Factor of Safety*

The overall integrity of the machine design can be established by ensuring that the factor of safety, which can be obtained using equation (9) and, is greater than 1.
This will guarantee that the machine will not collapse structurally under the action of loads.
FoS is the factor of safety, Y_S is the yield strength of the selected material for the machine frame, and W_S is the working stress or maximum stress?

$$FoS = \frac{Y_S}{W_S} \tag{10}$$

2.2.1.5 *Prime Mover Power Requirement*

Power = Force ×Velocity
Power = Force × Screw Circumference × rpm

$$W = P \times \pi DN/60 \tag{11}$$

2.2.1.4 *Shear stress on Farme*

To determine the thickness of the triangular bars of know width frame. The equation is given by;

$$S_r = \frac{S_e}{F_s} - \frac{S_e}{S_{yp}} \times S_m \tag{12}$$

S_r=Superimposed alternative stress

$$S_r = \frac{(\text{Maximum Stress} - \text{Minimum Stress})}{2}$$

Minimum stress = weight of the machine components on the frame
Maximum stress = all the weights above the plus weight of waste material filling the hopper and force exerted by the electric motor on the machine members.

2.3 Description of the Machine

The agricultural waste shredder consists of the following major component: Cutting blade, machine frame, sieves, hopper, waste collector, cover, and Belt cover as illustrated in figure 1a and figure 1b..

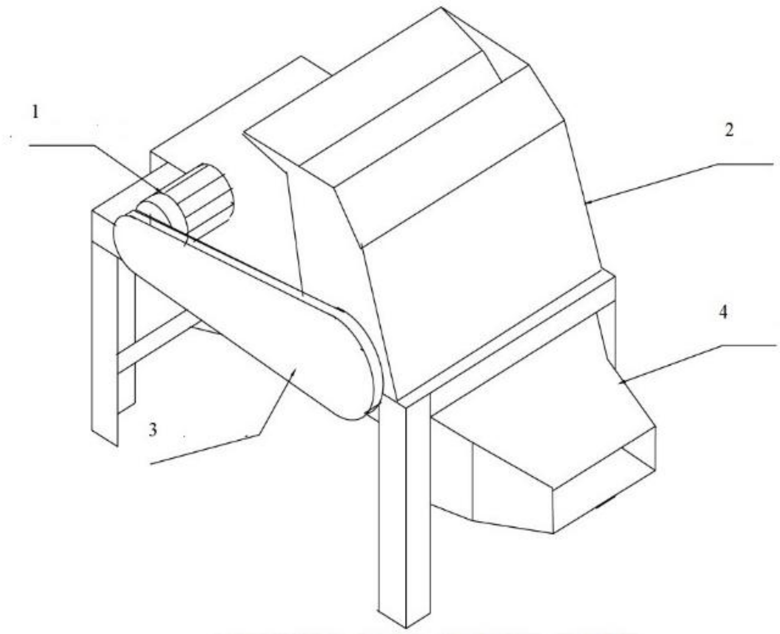

Figure 1a: Waste Shredding Machine Assembly

Figure 1b: Agricultural waste Shredder

1. Electric Motor
2. Shredder Hopper
3. Belt Cover
4. Shredder waste collector.

2.3.1 Shaft Assembly

Three 26mm diameters shaft were turned to size down to 25mm. A 440mm long was used to attach the shafts. Similarly, another shaft of 600mm long and 76mm diameter was also turned to 75mm. Two equilateral triangular plates of sides 130mm were cut with 2mm thickness. The cutting blades were welded on the cutting shaft at a spacing of 40mm apart. Finally, the driven shaft was positioned at the center of the triangular plates and welded together.

2.3.2 Machine Frame

The Frame was made up of mild steel of rectangular cross-section. the main function of the frame is to carry the weight of the machine components which include shafts, electric motor, the pulleys, and its cover the hopper, shredding chamber agricultural waste, sieve, and the collector assembly. To determine the thickness of the frame the procedure of (Black and Adams, 2000) from equation (9)

A 3mm thick steel plate with 50mm width was selected to avoid any underestimation.
70mm × 70mm was cut to various sizes. The pieces were welded together to form a rectangular of the machine. Angle iron of 50mm × 50mm was cut to sizes and welded underneath the framework as a brace to increase the strength of the frame. The frameset for the electric motor was formed and holes drilled.

2.3.3 Shredder Sieve

The sieve is be located underneath the cutting blade assembly housing. It allows small pieces of shredded waste materials of less than 20mm in length to pass through the holes. The endplates will be welded to the concave metal sheet, which has a series of Q20 holes. The taps drilled to provide holes for bolting the sieve unto the frame of the machine.

2.3.4 Hopper and Shredding Chamber

Waste shredder hopper was a combination of parallelogram prism and a shortened rectangular based pyramid, which was placed on the chamber that houses the shredder shafts.

The hopper is part of the machine with an opening at the top for feeding the waste materials for shredding. The volume of the shortened rectangular based pyramid hopper was determined using equation (4), while. The Parallelogram prism volume was determined using equation (5). The materials slide down the hopper and fall unto the cutting blade assembly. Hopper was constructed using 1mm mild steel sheet. Taps were provided, at the bottom of the hopper with holes to allow it to be bolted with 20mm diameter bolts and nuts onto the machine frame.

2.3.5 Shredded Material Collector

The collector is located at the bottom of the sieve to allow small pieces of shredded materials into it and to direct the shredded materials into the container for collection through the outlet. The collector was made from a 1mm thick mild steel sheet; it is also made with holes drilled in them for bolting it to the frame of the shredder.

2.3.6 Top cover

The top cover of the machine was constructed to cover the remaining top part of the framework of the machine. This part is constructed with a 1mm mild steel sheet by surface development. It is to be bolted onto the top part of the framework.

2.3.7 Belt cover

The belt cover is a guard against accidental contact with the operator due to the rotating Vee belt when the machine is in operation. It was constructed using 1mm mild steel sheet. The circular part of the small end of the belt cover was a bit larger than the electric motor pulley to allow the pulley to run freely without contact with it, likewise, the bigger end of the belt cover is a bit larger than the pulley of the cutting belt assembly. The various part of these components was joined together by welding's.

Bearings Selection

Readily available bearings were used since they have standard and cannot be constructed in the workshop. They were selected based on the required inner and outer diameter.

2.4 Cost of Production

A total cost of Fifty-Nine Thousand Seven Hundred Naira (₦59,700.00) was spent in the Construction of the Shredder. The breakdown is as follows:

S/N	Components	Qty.	Unit Cost (₦)	Total Cost (₦)
1	3mm mild steel sheet	1	11,000	11,000
2	1 mm mild steel sheet	1	9,000	9,000
3	Electric motor	1	18,500	11,500
4	Electric motor speed regulator	1	3,000	5,000
5	Pulleys	2	1,000	2,000
6	3mm (70mm x70mm) Angle Iron	2	1,800	3,600
7	Electrodes	2	1,800	3,600
8	Paint	1	1,500	1,500
9	Hinges	4	100	400
10	Bearing	2	1,500	3,000
11	Belts	2	400	800
12	Bolt and Nuts	20	30	600
13	Washers	20	10	200
14	Cutting disc	5	700	3,500
15	Grease	1	800	800
16	Binding wire	1	1,200	1,200
17	Transportation	1	2,000	2,000
18	Labour	1	5,000	5,000
	Grand Total			**₦59,700**

2.5 Performance Evaluation

The designed and fabricated waste shredding machine was tested to evaluate its performance on the basis of Shredding efficiency and throughput capacity. After construction and assembling the machine, the efficiency was further tested using the response surface methodology design of experiments (central composite design). MINITAB software version 19 was used to conduct the analysis. The experiment conducted for dry beanstalks and leaves. This test conducted at three speeds of 360rpm, 650rpm, and 975rpm with three (3) sieve apertures of 20mm, 30mm, and 40mm with total number of thirteen (13) runs. The coding for high, centre and low as -1, 0, and +1 to represent respectively. The coded and natural variables are illustrated in table 2.

Table 2: Independent variables and natural levels used for Central Composite Design

Variables	Low	Centre	High
Code	-1	0	+1
X_1	325	650	975
X_2	20	30	40

X_1 = shredding speed in rpm, X_2 = shredding sieve Aperture in mm.

3.5.1. Shredding efficiency

To determine the shredding efficiency the total weight of waste materials to be shredded was measured and recorded before shredding in the machine, similarly, the weight of both shredded and unshredded materials were measure and recorded. All measurement were made in Kilogramme (Kg). The shredding efficiency of the machine at three different speeds of shredding was determined as follows;

$$SE = \frac{W_c}{W_T} \times 100 \ (\%) \quad (13)$$

$$W_c = W_T - W_u \text{ (Kg)}, \quad (14)$$

Where,

SE = Shredding efficiency (%)

W_C = Weight of shredded materials (kg), and

W_T = Total weight of the waste (kg).

W_u = Total weight of shredded materials (kg).

3.5.2. *Throughput capacity*

The throughput capacity of the shredding machine was tested at the three different speeds of operation namely; 325rpm, 650rpm, and 975rpm respectively.

The throughput capacity was calculated using the following equation

$$TP_c = \frac{W_T}{T} \qquad (15)$$

Where,

W_T = total weight of the shredded waste. (kg)

T = time of operation(s)

3.0. Result and Discussion

The throughput capacity of the machine was tested and the results illustrated in Table 1. The result shows that the higher the speed of operation the higher the throughput capacity. At the speed of 975rpm, the machine was able to shred 6.10kg of agricultural materials, while at the lowest speed of 325rpm the total shredded material was 5.12kg, this agrees with the result of (Ayo et al., 2014).

Table 1: Throughput Capacity of Shredding

Operation speed (rpm)	Throughput capacity (kg/min)
325	5.12
650	5.69
975	6.1

Table 3: Design table (randomized) before response surface Analysis

Run Order	X_1 Coded	X_2 Coded	X_1 (rpm)	X_2 (mm)	W_C (kg)	W_T (kg)	Σ (%)	PFITS (%)
9	0	0	650	30	8.231	10	82	82.1724
4	1	1	975	40	7.993	10	80	80.4655
13	0	0	650	30	8.228	10	82	82.1724
2	1	-1	975	20	9.289	10	93	91.7989
11	0	0	650	30	8.201	10	82	82.1724
3	-1	1	325	40	7.794	10	78	79.1322
10	0	0	650	30	8.222	10	82	82.1724
12	0	0	650	30	8.311	10	83	82.1724
6	1	0	975	30	8.511	10	85	85.7356
7	0	-1	650	20	8.612	10	86	87.7356
5	-1	0	325	30	8.416	10	84	83.4023
8	0	1	650	40	7.901	10	79	77.4023
1	-1	-1	325	20	8.903	10	89	88.4655

Table 4: Regression Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	82.172	0.508	161.63	0.000	
X_1	1.167	0.500	2.33	0.052	1.00
X_2	-5.167	0.500	-10.34	0.000	1.00
X_1*X_1	2.397	0.737	3.25	0.014	1.17
X_2*X_2	0.397	0.737	0.54	0.607	1.17
X_1*X_2	-0.500	0.612	-0.82	0.441	1.00

The results of the model explains 94.78% of the variation in shredding efficiency. However, the R^2 (pred) of 70.42% suggests that the model is fit. If additional models are fitted with different predictors, use the adjusted R^2 values and the predicted R^2 values to compare how well the models fit the data as shown in table 5.The developed coded responses functions of the machine investigated are as follows

$$\text{Efficiency (\%)} = 82.172 + 1.167x_1 - 5.167x_2 + 2.397x_1^2 + 0.397x_2^2 - 0.500x_1x_2 \quad (16)$$

Table 5: Model Summary

S	R-sq	R-sq (adj)	R-sq (pred)
1.22441	94.78%	91.06%	70.42%

The regression effects of Shredding speed and shredding aperture for both the linear, square, and interaction on efficiency. The result indicated that the speed with which the shredder was operated did not have any significant effect on the shredding efficiency with a p-value of 0.052. This concludes that there is no statistically significant association between the efficiency and the speed of operating the shredder. Although the Aperture diameter was significantly affecting the efficiency at 5% level of significance (p = 0.000). The square model for speed indicated a significant effect, which also concludes that there is a statistically significant association between the efficiency and the square of the speed, while the square of shredding aperture did not show any significant effect on the efficiency. The two-way interaction between the speed and aperture did not show any significant effect on the shredding efficiency as shown in table 6.

Table 6. : Response Surface Regression efficiency versus speed and aperture of shredding Machine

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	190.737	38.147	25.45	0.000
Linear	2	168.333	84.167	56.14	0.000
X_1	1	8.167	8.167	5.45	0.052
X_2	1	160.167	160.167	106.84	0.000
Square	2	21.403	10.702	7.14	0.020
X_1*X_1	1	15.863	15.863	10.58	0.014
X_2*X_2	1	0.434	0.434	0.29	0.607
2-Way Interaction	1	1.000	1.000	0.67	0.441
X_1*X_2	1	1.000	1.000	0.67	0.441
Error	7	10.494	1.499		
Lack-of-Fit	3	9.694	3.231	16.16	0.011
Pure Error	4	0.800	0.200		
Total	12	201.231			

The Pareto plot shows the effects of speed and aperture in figure 2. This shows the visual identification of the important effects and compares the relative magnitude of the various effects. In addition, it shows that the largest effect is shredding aperture (B) because it extends the farthest while, Aperture*Aperture (BB) is the smallest because it extends the least.

The regression coefficient as illustrated in table 4 shows that the coefficient for shredding speed is not significant (1.167, P=0.052), this conclusion that all level means for speed are equal. The coefficient for a shredding aperture was significant (-5.167, p=0.000), and concludes that not all level means for speed is equal. Similarly, the coefficient for squared aperture has shown no significant effect (0.397, p=0.607). This concludes that the relationship between the aperture and the efficiency does not follow a curved line, while the coefficient for a squared speed was having a significant effect on efficiency (2.397, p=0.014), this concludes that the relationship between the aperture and the efficiency follow a curved line.

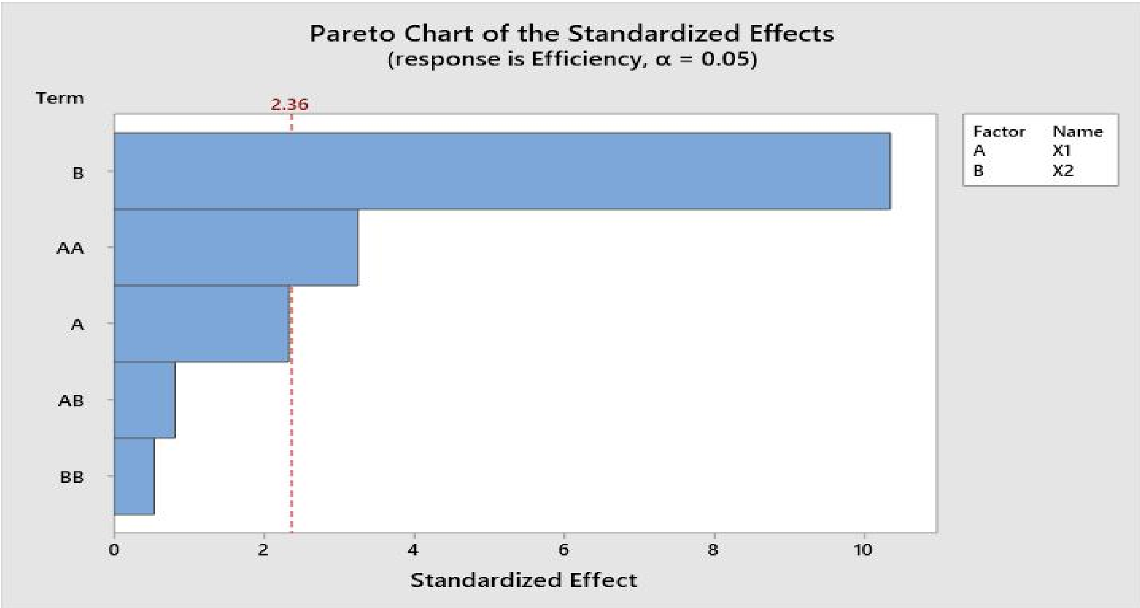

Figure 2: Pareto chart for the effect of speed and aperture on the efficiency of shredding Machine

However, the coefficient for interaction for shredding speed and aperture was not significant (-0.500, p = 0.441), the relationship between speed and the efficiency does not depend on the other all the factors in the term.

4.0 Conclusion

An agricultural waste shredding machine was developed using locally available materials. The machine performed satisfactorily with better efficiency during the test run. Results from the test showed that the size of the shredding aperture of the machine significantly affected the shredding efficiency of the machine. The shredding efficiency of the machine decreased with increasing shredding aperture but increased with shredding speed. Maximum shredding efficiency of 93% was achieved when the shred aperture was 20mm and the shredding speed was 975rpm. The throughput capacity of the machine increased with the speed of shredding with a maximum value of 6.10kg kg/m at 975rpm and a minimum value of 5.14kg/m at 325rpm.

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