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Design, fabrication and evaluation of a screw type pelletizer with an interchangeable auger

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ABSTRACT

Pellet and Briquettes are becoming of increasing importance and this is attributed to the variety of purposes which are used as cheaper, portable, more effective variation of their source materials and can be produced by using densification equipment. The cost of these densification equipment can be relatively expensive, thus the need to produce them locally arises. There is also an avenue for modification which makes the locally fabricated pelletizer better than the imported pelletizers. The augers are detachable from the shaft thus creating an opportunity to vary the screw configuration. The interchangeability of the pelletizer also reduces the cost of replacement of the shaft as only the augers can be replaced. The machine was designed and fabricated based on component design consideration using mild steel as a major component which is a readily affordable and available. Preliminary evaluation of the pelletizer yielded a Pelleting Efficiency of 53.69% and a Percentage Recovery of 54.87%.

Keywords: Pelletizer, Interchangeable Auger, Design, Modification

1. INTRODUCTION

Processing machines have over the years been used to add values to agricultural materials and they come in varieties depending on their functions and desired output. Machines used in agglomeration, size reduction, drying, cooking, conveyance, stowage, mixing and separation are commonly available (Saravacos and Maroulis, 2011; Saravacos and Kostaropoulos, 2002). This implies there is need for continuous research, development and modification of these processing equipment in lieu to enhance efficiency, effectiveness and ergonomics. The screw type pelletizer has evolved to be one of the most versatile agglomeration equipment and encompasses mixing, conveying, cooking, moulding and cutting. It is currently used for a wide range of activities which include animal feed production (Fahrenholz, 2012), fuel generation (Ahn et al., 2014), biomass compaction (Djatkov et al., 2018; Shaw, 2008) by-products (Jan et al., 2016), flour-based snacks (Pichmony and Girish, 2020) and composite materials (Forero-Nuñez et al., 2015).

The process of extrusion is often preceded by size reduction often achieved by shredding, milling or crushing (Kadiri, 2014; Ma et al., 2020). Densification is necessary to improve handling, packaging, transportation, storage, combustion, animal health, uniform mass and sizes of snacks and pharmaceutical goods, reduce exposure to dust as well as a deduction in labour costs (Gilvari et al., 2019). According to Saravacos and Kostaropoulos, (2002), certain economic considerations (consistency of the cost of the screw extruder, affordable and readily available binders and other additives, low energy consummation, low wear and tear and affordable and readily available component parts) and technical criteria (low noise level 85 Decibels (85db), minimal loss of extrudate, optimal capacity of the machine, optimal quality of the product must be achieved, a strong foundation to withstand vibrations) should be met in the selection of the extruder. One important goal of fabricating and designing these machines locally is to effectively produce economically viable equipment capable imitating imported machines while utilizing lesser power, smaller in size, cheaper to manufacture and easier to maintain and repair.

2. DESIGN CONSIDERATIONS

The pelletizer was constructed majorly using mild steel as a major construction due to its affordability and resilience. It was modelled after the AutoCAD diagram in Figure 1 and encompasses hopper design.

Hopper Design

According to (Kadiri, 2014; Aremu et al., 2014), the hopper will be calculated using Equation (1)

$$V_H = \frac{C_M(m^3/hr)}{N_C(min/hr)} \times F_S$$

Where V_H is the Volume of the Hopper

C_M is the capacity of the Machine

N_C is the frequency of which the hopper would be reloaded per minutes (in Hours)

Fs is Factor of safety (1.5).

The capacity of the machine CM can however be obtained from the equation

$$C_M = \frac{Feed\ Rate}{Bulk\ Density\ of\ the\ Mixture}$$

Ugoamadi, (2012) stated that the relationship volume of the hopper, the height of the hopper and the size of the openings at both ends of the hopper for a frustum of a pyramid is represented by equation 3

$$V_H = \frac{h}{3}\left[A_1 + A_2 + \sqrt{A_1 A_2}\right]$$

Where h is the height of the hopper

A_1 is Area of the opening at the top of the hopper

A_2 is Area of the orifice at the bottom of the hopper

Screw and Barrel Design

Bortolamasi and Fottner, (2001) specified that the screw pitch is correlated to the screw diameter at the feeding section by the formula

$$D_S = \frac{3}{2}P_S$$

$$d_S = \sqrt{\left(D_S^2 - \frac{4Q}{\pi \times P \times N \times f \times 60}\right)}$$

Where Q = Rate of input m^3/hr

D_s = Barrel Diameter

d_s = Minor Diameter of Screw conveyor

P= Pitch

f= Feed Material

N= Speed of the pelleting

Q is obtained from

$$Q = \frac{\text{Input}}{\text{Density of Preconditioned Mixture}}$$

Helix angle

$$\theta = cos^{-1}\left(\frac{D_b - D_{sh}}{D_{sc}}\right)$$

Where D_b = Diameter of Barrel

D_{sh} = Diameter of Shaft

D_{sc} = Diameter of Screw Conveyor

But D_{sc} is the difference between barrel diameter and Minor diameter of screw conveyor. Oduntan et al., (2014) revealed that the length of the conveyor can be obtained via the mathematical expression

$$S = 3.42(r + ml)\theta$$

Where r is the radius of the shaft (m)

m is the tangent of the tapering angle

θ is the helix angle (rads)

l is the length of the shaft (m)

Belt and Pulley System

The pulley system was designed in accordance with Kadiri, (2014) and Aremu et al., (2014)

$$N_1D_1 = N_2D_2$$

Where N_1 = Speed of the Pulley on the motor

D_1 = Diameter of the Pulley on the motor

N_2 = Speed of the Pulley on the Gear box

D_2 = Diameter of the Pulley on the Gear box

Similarly, the length of the belt was determined by

$$L = \frac{\pi}{2}(D_1 + D_2) + 2x + \frac{(D_1 - D_2)^2}{4x}$$

Where D_1 = Sheave diameter of pulley on the motor

D_2 = Sheave diameter of pulley on the Gear box

L = Belt length

x = Distance between the centres of driving and driven pulleys

Shaft Design

The shaft's diameter according to (Odesola et al., 2016; Oduntan et al., 2014; Ugoamadi, 2012; Khurmi and Gupta, 2005) can be obtained using equation below

$$D = \sqrt[3]{\frac{16}{\pi\tau}\left(\sqrt{(K_bM_b)^2 + (K_tM_t)^2}\right)}$$

Where τ = Maximum Allowable Stress of the Shaft material

K_b = combined shock and fatigue factor for bending

K_t = combined shock and fatigue factor for twisting

M_b = Maximum bending moment on the shaft

M_t = Maximum twisting moment on the shaft

Power Requirement

The Power requirement according to (Ugoamadi, 2012) can be mathematically obtained from the equation below

$$P(hp) = \frac{E_T \times K_S}{746}$$

Where E_T is total energy required for the pelleting process

K_S is Service Factor

But $E_T = E_S + E_R + E$

Where E_S is Energy required to convey the extrudate along the screw

E_R is the energy required to rotate the shaft

E is energy required to push the extrudate through the die

According to (Odesola et al., 2016), E_S is calculated from the equation

$$E_s = 8M\left(\frac{\pi N}{60}\right)^3 r^2$$

Where M is the mass of the shaft
N is rotational speed of the shaft
R is the radius of the shaft
Odesola et al., (2016) also stated that ER can be derived from the formula below

$$E_R = \frac{QL}{367}(\omega_o + sin\,\beta)$$

Where Q = Feed Rate (120 kg/hr)
L is Length of Screw conveyor (0.5834m from 3.1.1)
ω_o is conveyance constant (4.0 for slow-flowing abrasive material)
β is angle of inclination for the barrel (0°)
E, the energy required to push the extrudate through the die can be derived from the mathematical expression

Further Modification

A composite shaft was recommended to make the auger interchangeable. This innovation has two advantages

The cost of replacing the screw augers due to wear and tear is reduced.

There is an opportunity of choosing and experimenting other screw configuration such as a change in screw pitch, a change from constant to variable screw pitch (Rokey, 2000).

The pelletizer was modified to enable a change in the screw auger, this was achievable by constructing the augers on removable pipes which can be attached to the main shaft via keys and keyways. The dimension of the key was determined in accordance with the standard IS: 2292 and 2293-1974. Table 1 depicts the standard proportion for standard parallel, tapered and gib keys (Khurmi and Gupta, 2005).

Evaluation of the Pelletizer

Grounded kenaf stems were manually mixed with cassava starch in ratio 1:1 and water 1:3 as extrudates and used in the production of pellets. The pelletizer was evaluated in accordance with procedures stipulated in Davies and Davies, (2011), Ojomo et al., (2010) and Aremu et al., (2014) using Pelleting efficiency and percentage recovery as benchmarks.

Pelleting Efficiency

The Pelleting Efficiency is the tendency of the pelletizer to produce pellets and it can be mathematically attained using the equation below

$$\eta\ \% = \frac{M_P}{M_T} \times 100\%$$

Where η is the Pelletizing Efficiency
M_P is the mass of pellets produced by the machine
M_T is the mass of output

Percentage Recovery

Percentage Recovery is the proportion of the Kenaf mixture recovered after each trial. It is obtained using Equation below

$$R(\%) = \frac{M_o}{M_T} \times 100\%$$

Where *R%* is the Percentage Recovery
M_O is the Mass of the Output
M_T is the mass of Input (Kenaf and Binder)

Table 1 Standard key dimensions for Shaft sizes

Shaft diameter (mm) up to and including	Key cross-section		Shaft diameter (mm) upto and including	Key cross-section	
	Width (mm)	Thickness (mm)		Width (mm)	Thickness (mm)
6	2	2	85	25	14

8	3	3	95	28	16
10	4	4	110	32	18
12	5	5	130	36	20
17	6	6	150	40	22
22	8	7	170	45	25
30	10	8	200	50	28
38	12	8	230	56	32
44	14	9	260	63	32
50	16	10	290	70	36
58	18	11	330	80	40
65	20	12	380	90	45
75	22	14	440	100	50

3. RESULTS

The pelletizer was constructed based on the prelisted design calculations and in resemblance to the AutoCAD model depicted in Figure 1. Plate 1 shows the pelletizer, Plate 2 portrays spare augers while the picture of the shaft, key and auger is portrayed in Plate

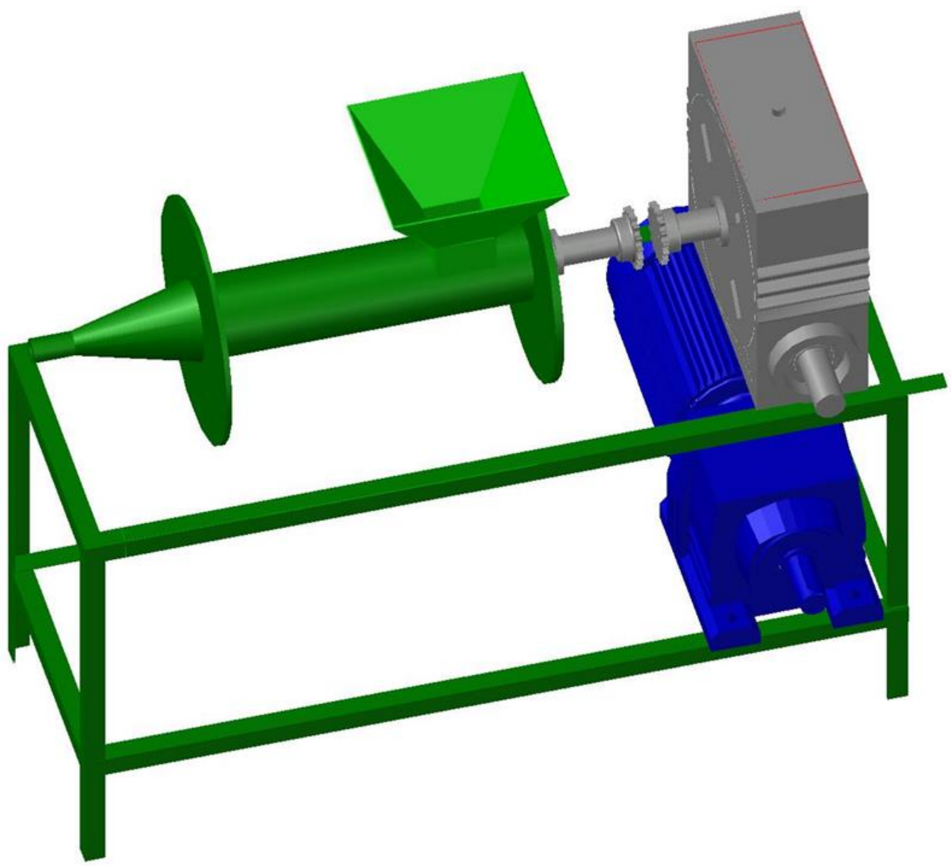

Figure 1 AutoCAD Model of the Pelletizer

Plate 1 The Screw-type Pelletizer

Plate 2 Spare Interchangeable Augers for the Pelletizer

Physical Appearance and Configuration of the Pelletizer

A frame was constructed from 2 inches wide angle iron. The hopper and barrel were welded together as a single unit, a cone with a die was fitted at the end. A speed reduction gearbox was placed on the frame whereas a 3-horsepower electric motor was placed under the frame and connected to the gearbox via belt and pulleys. The main shaft was made from high carbon steel alloy and machined in such that a keyway 16mm wide and 10mm deep was made on the shaft. A key of square cross-sectional area of 16mm by 16mm and length three-quarters of the detachable augers was made. The detachable augers made from mild steel were attached to the main shaft via the key. The gearbox and the shaft were coupled together via sprockets and double chain. There is also a pair of support pillow bearings which hold the shaft on the frame.

Plate 3 Key, Shaft and one of the Augers

Preliminary Evaluation Results

The performance of the pelletizer was evaluated using equations in section 2.7. The following figures were obtained from the run of the machine.

Mass of grounded kenaf = 200g

Mass of water added= 600g

Mass of Starch powder= 200g

Total mass of Input = 1000g

Unpelleted Mass= 11.8g

Mass of Pellets = 536.9g

Time for input to finish in the Hopper = 10 minutes 45 Seconds

Pelleting Efficiency

The Pelleting Efficiency can be determined as

$$\eta\ \% = \frac{M_P}{M_O} \times 100\%$$

$$\eta\ \% = \frac{536.9}{1000} \times 100\%$$

$$= 53.69\%$$

Percentage Recovery

Percentage Recovery of the Pelletizer was obtained

$$R(\%) = \frac{M_o}{M_T} \times 100\%$$

$$R\% = \frac{548.7}{1000} \times 100$$

$$= 54.87\%$$

Additional Evaluation

The pelletizer was further evaluated at 5 various speeds (40, 50, 60, 70 and 80 RPM), producing pellets of 5 diameters (27.5, 30.0, 32.5, 35.0 and 37.5mm), having 5 kenaf/starch ratio (1:1.00, 1:1.25, 1:50, 1:1.75 and 1:2.00) using augers with 5 different screw pitches (40, 50, 60, 70 and 80mm). The experiment schedule was designed using central composite design, an element of Response surface methodology obtained in Design Expert Software version 10. The machine performance was assessed based on the formulae in section 3.2 and presented in Table 2 below. The results were analysed using Support Vector Machines tool, a tool in MATLAB R2021a.

Table 2 Evaluation of the Screw pelletizer using Various parameters at 5 levels

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2
Std	Run	A: Screw Pitch	B: Die Size	C: Pelleting Speed	D: Starch/Kenaf Ratio	Pelleting Efficiency	Percentage Recovery
		mm	mm	rpm		%	%
17	2	40	32.5	60	1.5	92.14	85.6
18	3	80	32.5	60	1.5	92.84	84.93
10	5	70	30	50	1.75	93.87	77.98
1	6	50	30	50	1.25	92.62	73.95
8	7	70	35	70	1.25	91.55	71.92
27	8	60	32.5	60	1.5	91.62	82.36
12	9	70	35	50	1.75	94.81	80.26
25	10	60	32.5	60	1.5	91.62	82.36
2	11	70	30	50	1.25	90.68	70.03
13	12	50	30	70	1.75	93.66	82.98
7	13	50	35	70	1.25	94.03	75.49
23	14	60	32.5	60	1	95.06	86.88
14	15	70	30	70	1.75	91.72	74.88
21	16	60	32.5	40	1.5	90.97	78.45
5	17	50	30	70	1.25	89.61	75.21
26	18	60	32.5	60	1.5	91.62	82.36
3	19	50	35	50	1.25	85.74	69.94
9	21	50	30	50	1.75	90.47	82.22
6	22	70	30	70	1.25	92.66	83.74
29	23	60	32.5	60	1.5	91.62	82.36
20	24	60	37.5	60	1.5	82.36	68.49
30	25	60	32.5	60	1.5	91.62	82.36
4	26	70	35	50	1.25	85.96	70.85
11	27	50	35	50	1.75	90.63	87.36
19	28	60	27.5	60	1.5	88.76	82.59
28	29	60	32.5	60	1.5	91.62	82.36
22	30	60	32.5	80	1.5	92.46	73.89
16	1	70	35	70	1.75	95.6	87.05
24	20	60	32.5	60	2	95.62	88.27
15	4	50	35	70	1.75	95.76	81.18

The details of analysis are enumerated below

Model Type

Preset: Optimizable SVM

Kernel scale: 1

Optimizer Options

Optimizer: Bayesian optimization

Acquisition function: Expected improvement per second plus

Iterations: 30

Training time limit: false

PCA

PCA: Enabled

PCA is keeping enough components to explain 95% variance.

After training, 2 components were kept.

Explained variance per component (in order): 48.5%, 48.5%, 3.0%, 0.0%

Other information explicit to each evaluation basis are presented in Table 3

Table 3 Data Analysis results

	Pelleting Efficiency		Percentage Recovery	
Criteria	Training Results	Test Results	Training Results	Test Results
RMSE	2.9334	2.8532	5.6727	5.1265
R-Squared	0.14	0.06	0.07	0.19
MSE	8.6047	8.1409	32.18	26.281
MAE	1.9985	1.8898	4.8011	3.9053
Prediction speed	~310 obs/sec		~370 obs/sec	
Training time	175.3 sec		175.25 sec	
Optimized Hyperparameters	Kernel function: Linear Box constraint: 0.0010261 Epsilon: 0.013496 Standardize data: False		Kernel function: Gaussian Kernel scale: 0.0010066 Box constraint: 2.4875 Epsilon: 2.6412 Standardize data: False	
Hyperparameter Search Range	Box constraint: 0.001-1000 Kernel scale: 0.001-1000 Epsilon: 0.002209-220.9044 Kernel function: Gaussian, Linear, Quadratic, Cubic Standardize data: True, false		Box constraint: 0.001-1000 Kernel scale: 0.001-1000 Epsilon: 0.0060044-600.4448 Kernel function: Gaussian, Linear, Quadratic, Cubic Standardize data: True, false	

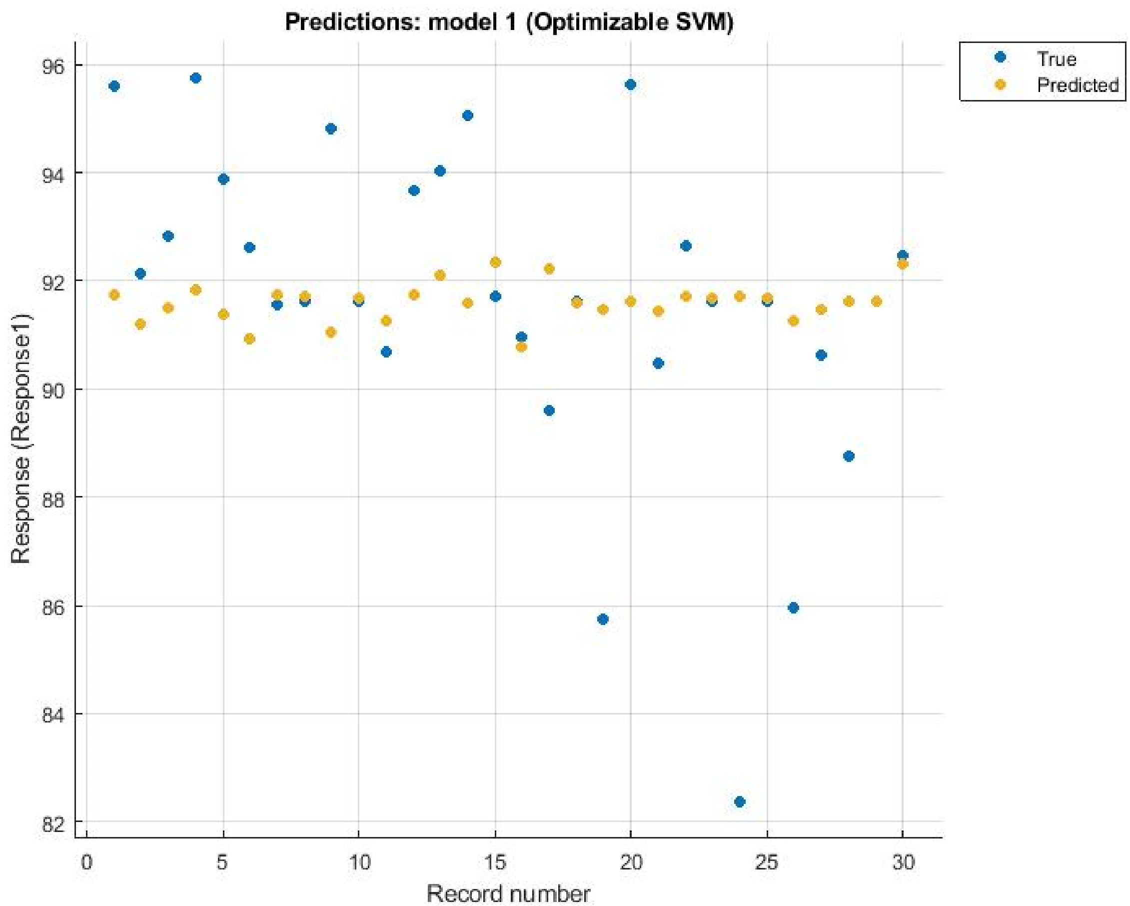

Figure 2 Pelleting Efficiency plotted against Trials

4. DISCUSSIONS

An initial evaluation of the extruder revealed Pelleting Efficiency (PE) of 53.7% when 200g of kenaf was used. However, variations in parameters coupled with increase in kenaf trial mass from 200g to 600g resulted in PE values within the range 82.3-95.8%. Root Mean Square Error (RMSE) were 2.9334 and 2.8532 for training and testing data, congruently. coefficient of determination (R^2) was 0.14 and 0.06 for trained and tested data respectively. Mean Absolute Error (MAE) were 1.9985 and 1.8898 for training and testing, correspondingly.

Preliminary evaluation of the extruder also revealed initial value of 54.9% for Percentage Recovery (PR) when a sampling kenaf mass 200g was used. However, alterations in the machine and operating parameters as well as an increment of sampling mass to 600g resulted in increase in PR values to 68.5-88.3%. RMSE values were 5.6727 and 5.1265 for trained and tested data, respectively. R^2 were 0.07 and 0.19 for training and tested data, harmoniously. MAE were 4.8011 and 3.9053 for trained and tested data.

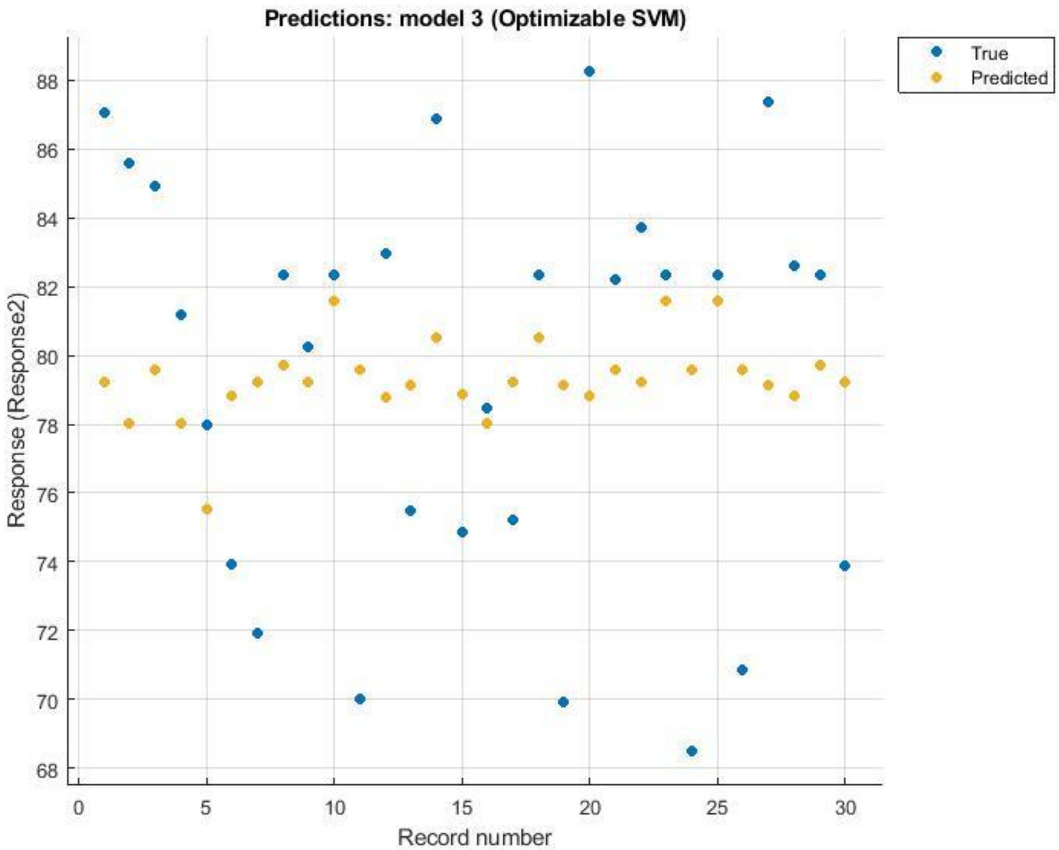

Figure 3 Percentage Recovery plotted against Trials

5. CONCLUSION

Credit Authorship Contribution Statement

Oluwaseun Kadiri**-** Writing, Design, Resource sourcing, investigation, analysis. Ademola Aremu- Supervision, coordination, technical assessment and review.

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Ethical issues

Not applicable.

Informed consent

Not applicable.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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