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Nonlinear simulation and optimization of oil palm bunch stripping machine

M.C. Onwukwe[a], B.N. Nwankwojike[a], and John Chijioke Edeh*[b]

[a]Enugu State University of Science and Technology, Enugu, Nigeria
[b]Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria

Abstract

A developed oil palm stripping machine was evaluated; optimizing its performance in oil palm bunch stripping. The operational parameters considered were the rotary speed of the machine, mass of loaded oil palm, length of the stripping shaft, number of beaters and stripping time while the stripping efficiency, throughput capacity and specific energy consumption of the machine constituted performance parameters. A two level half factorial central composite design was employed in the development of empirically based non linear models for predicting the performance responses. The developed models were used to optimize the performance using the MOSQP solver for non linear programming. It was established that the optimal factor settings of the machine were 438rpm, 45kg, 2625mm, 8 beaters and 540 seconds for the machine speed, mass of loaded palm bunch, shaft length, number of beaters and stripping time respectively. The optimal performances at these factor settings were 84.2%, 225kg/hr and 57.51kJ/kg at an optimality rate of 91%, 99.1% and 97.2% for the stripping efficiency, throughput capacity and specific energy consumption respectively with overall optimality value of 95%. Also, confirmatory test results showed that the machine when operated at the optimal settings gave values close to the predicted optimal results at 95% confidence level. With these models, oil palm bunch stripping machine were characterized and rated for increased productivity and earnings in oil palm processing sector.

Keywords: Oil palm fruit; stripping; performance parameters; non linear model; optimal settings

1. Introduction

Oil palm *(Elaeis guineensis)* is the highest oil yieldding crop compared to other oil bearing crops. The oil palm produces its fruit in bunch (Fig. 1a) consisting of several oval-shaped drupe fruits (similar in size to a small plum) of 6-20 grams attached in stalks [1]. This individual palm fruit (Fig. 1b) when stripped from the bunch (leaving empty bunch shown in Fig. 1c) is made up of the pericarp (fibrous oil matrix pulp) and a central nut (kernel nut). The pulp (mesocarp and exocarp) contains the palm oil while the nut consists of an endocarp shell concealing the kernel that contains palm kernel oil [2]

The palm and kernel oil are product of oil palm with over 80% food products utilization whereas the remaining parts serve as feed stock for other non-food applications [3]. Empty bunches (Fig. 1c) and fibers among the by-products of oil processing could be further processed for production of potash fertilizer, pulp and paper manufacturing [4,5].

However, prior to processing the oil palm, the palm fruits must be detached from the palm bunch in a process known as stripping or threshing. The traditional palm fruit threshing method involves cutting the fresh fruit bunch (FFB) into sections and picking off of loosed fruits from the sections by hand after 2 to 4 days [6]. This crude technique is inefficient, time consuming and arduous [7] with resultant low output. It has become inappropriate in the wake of technological and industrial revolution as the need for efficient oil palm threshing among oil palm processors increases with the need for good quality processed oil palm product. Nevertheless, to ensure high oil extraction up to 87% with better quality oil at low fatty acid and carotenoid content, [8] observed that processing of fresh fruits without delay or fermentation was apt and recommendable. This implies that immediate and timely processing of fresh fruit bunches prevents rapid rise in free fatty acid which normally affects the quality of the crude palm oil [8,9]). [7] also observed that shortages in palm oil production were traceable to huge energy requirement in the processing especially in the preprocessing operations such as the threshing procedure. These necessitated mechanization of the oil palm stripping process.

Most of the mechanized palm fruit bunch stripping systems consist of a rotating drum or fixed drum equipped with rotary beater bars which detach the fruits from the bunch, leaving the stalks on the stem [3]. Regrettably, some of these oil palm strippers are usually expensive and unaffordable by the local farmers who constitute the critical mass of the sector since majority of the machines are imported into the country. This led to the development of oil palm strippers by NIFOR, Benin, indigenous researchers and the Project Development Institute (PRODA), Enugu. However, products processed with the existing palm fruit strippers are often incompletely stripped in addition to fruit fibre contamination of end product which consequently results in reduced oil content quality. Bunch stripper also has deficiency in terms of stripping time, efficiency and productivity occasioned by variation in fruit adherence to the palm bunch across varieties, level of ripeness thus resulting in drudgery and time consuming pre-treatment of the palm bunch (sterilization). Incomplete stripping of the oil palm fruit from the bunch, smashing of the fruit due to excessive striping force and the inclusion of chaff particles with the oil palm fruits which significantly undermines the quality of the palm oil further limit efficient mechanical stripping process. As an attempt in addressing the aforementioned challenges, an improved palm fruit stripping machine was developed and experimented in PRODA

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*Corresponding author. Email: engredehjohnc@gmail.com

Figure 1: (a) Palm fruit bunches (b) Stripped fruits (c) Empty bunch

Experimental investigations showed that variation of crop and machine/operational parameters affects the performance of the machine though the levels of impact were not readily determined. To improve performance, machine of this nature is required to perform, keeping specific energy consumption at minimum for maximum efficiency and throughput, possible. The stripping efficiency as expressed by [4] was the ratio of the total weight of stripped palm fruit to the total weight of palm fruit in the bunch before stripping. This was further modified to account for the fruit left in the bunch after stripping as the ratio of the total mass of stripped palm fruit to the sum of the stripped palm fruit and the mass of palm fruit left (retained) in the bunch after stripping by the machine. Throughput is the mass of properly stripped palm fruits discharged by the machine per unit time. Stripping time is the total resident time of the oil palm bunch in the machine from loading to unloading at the discharge chute while the specific energy requirement of the machine is the electric power energy consumed per unit mass of stripped palm fruit. Also, a contributing factor to the inefficient stripping process is the fabrication and operation of the stripping machine at its suboptimal settings. Mechanical and operational factors such as the length of the stripper shaft, number of strippers (or beaters), inclination of the strippers (helix angle), species of palm fruit, size/geometrical properties of the palm bunch and operating speed of the machine significantly affect the energy consumption, throughput capacity, stripping time and efficiency of the machine. Hence, there was need for the performance analysis and prediction of optimal levels of operational parameters of this machine in order to ensure efficient operation.

Development of models and optimization with the operational parameters of the palm stripping machine requires an empirical optimization approach since multiple levels of machine performance parameters are dependent on varying combinations of input parameters. In such optimization problem, nonlinearity is anticipated for a multiple factor multiple response approach [10]. The technique involves unique experimental designs tactic requiring limited number of experimental runs in cost and time savings [6,11] while the objective function and/or some or all of the constraints are nonlinear functions [12]. Such empirical approach was used by [13], to fit mathematical models at 97.2% prediction on the effects of cutting speed, feed rate and cutting edge angle on the surface roughness and tangential force during AISI 1045 steel turning operation. NIST Physics Laboratory applied it to determine the best settings of seven factors that maximized *Sono* luminescent light intensity [11]. [14] developed a 96.82% prediction equation while relating operational characteristics (cutting speed, feed rate, depth of cut and surface roughness) in AISI 4140 steel turning process. [15] optimized mechanical clothing tactile comfort (thickness and fabric weight) to 98% success using empirical method. [16] applied empirical approach also in optimizing the effect of anti- obesity in fermented milk using lactobacillus plantarum Whereas, [17] applied empirical modelling and optimization to determine the optimal parameters for heavy end recovery in a centrifugal pump. [18] determined optimal mix proportions of standard ready mixed concrete. Thus, this study adopted mathematical modeling and empirical optimization in an oil palm fruit stripping machine with a view of improving its performance.

2. Materials and method

2.1. Machine description

The machine consists of component as shown in Fig. 2. Stripping operation is done by the beaters (rectangular bar) welded on revolving heavy shaft of the stripper. When bunch is loaded into the stripping unit of the machine, the revolving stripper shaft causes the entire bunch to be agitated by the feed forward sinusoidal motion of the oil palm bunch. This agitation (or stripping action) causes oil palm fruits to detach from the bunch and fall through the slit provided in the stripping unit into the separation chamber through the discharge chute while the empty palm bunch is carried to the stalk discharge section for unloading.

At the separation chamber of the discharge chute, a rotary bucket shaped section with small openings allows the passage of chaff and bunch particles which are unwanted in the final product. This chamber ensures that only oil palm fruits properly threshed from their bunch are collected from the discharge chamber.

The test performance indicators of the oil palm stripping machine are the stripping efficiency, throughput capacity, and specific energy consumption. Equations 1- 3 are the mathematical relationship used for computing these performance parameters from experimental data.

$$\eta_s = \frac{M_{\text{sf}}}{M_{\text{sf}} + M_{\text{rf}}} \times 100 \tag{1}$$

Where M_{sf} and M_{rf} are total mass of stripped palm fruit and mass of palm fruit retained in the bunch, kg respectively.

$$TP = \frac{M_{\text{sf}} + M_{\text{eb}}}{t_s} \tag{2}$$

Where TP is the throughput capacity, kg/s, M_{f} and M_{eb} are total mass of stripped palm fruit and mass of empty bunch in kg, while t_s is the stripping time in seconds

$$SE = \frac{Pt_s}{M_f} \tag{3}$$

Where SE is the Specific Energy in kg/s, while P and M_{f} are the power consumed by the electric motor in W and total mass of stripped palm fruit in kg respectively.

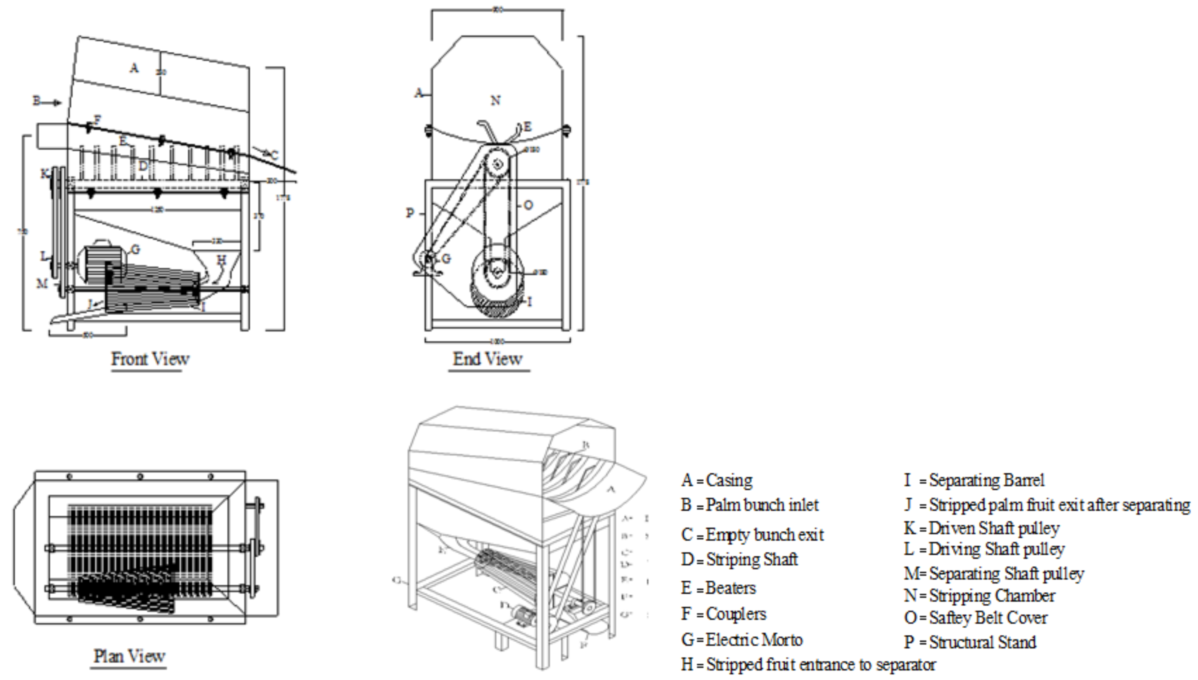

Figure 2: Oil palm stripping machine.

2.2. Experimental procedures

Effects of the operational parameters on the performance parameters were studied. Minitab® Release 17 software [19] was used to generate a two level, high (+1) and low (-1) factorial design in addition to the midpoint (0) of the factors. The two-level half factorial design $\left(\mathrm{nf} = 2^{k-1}\right)$ of completely randomized central composite design with six centre points, five factors and ten axial points totaling thirty-two (32) experimental runs (Table 1) was employed. The choice was based on its economic viability, desirable properties, and permission of marginally small experimental runs usually analyzed for high factorial points [20]. The experimental study variable (factor) number (K = 5), and these independent variables: the stripping shaft length (L), mass of the palm bunch (M), speed of stripping shaft (N), number of beaters (B) and time of stripping (T) were used for the design and analyses of the results. Experimental variation of the investigated factors against performance indicators were used to establish the factor limits. The determined high and low levels of each factor selected was based on convergence of the performance parameters or their indicated asymptote behaviour before or after some variables combinations. These tests were conducted at design settings/ values of 25 kg, 1500 mm, 350 rpm, 15 and 300 secs for the mass of palm fruit bunch loaded, shaft length, speed of the machine, number of beaters and stripping time respectively.

With the central composite design, the combination of high (+1), low (-1), centre point (0) and axial point (2.66) for each experimental run were evaluated and transformed to its natural value using the transformation Equation 4.

$$x = \frac{x - \left(\frac{x_{\max} + x_{\min}}{2}\right)}{\left(\frac{x_{\max} - x_{\min}}{2}\right)} \tag{4}$$

Where x is the independent variable in natural units; x is the coded variable while $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the independent variables respectively.

Then, the responses of stripping efficiency (η), throughput capacity (TP) and specific energy consumption (SE) were computed from the results of the factorial runs using the natural factor levels to first fit linear functions (main effects) of the performance indica-

Table 1: Composite design layout of factors.

Std Order	Run Order	Coded Factors				
		N	m	L	B	T
32	1	‘0	0	0	0	0
6	2	1	-1	1	-1	1
15	3	-1	1	1	1	-1
20	4	0	2	0	0	0
7	5	-1	1	1	-1	1
28	6	0	0	0	0	0
22	7	0	0	2	0	0
24	8	0	0	0	2	0
17	9	-2	0	0	0	0
3	10	-1	1	-1	-1	-1
27	11	0	0	0	0	0
18	12	2	0	0	0	0
2	13	1	-1	-1	-1	-1
26	14	0	0	0	0	2
16	15	1	1	1	1	1
31	16	0	0	0	0	0
13	17	-1	-1	1	1	1
23	18	0	0	0	-2	0
12	19	1	1	-1	1	-1
30	20	0	0	0	0	0
9	21	-1	-1	-1	1	-1
14	22	1	-1	1	1	-1
11	23	-1	1	-1	1	1
4	24	1	1	-1	-1	1
1	25	-1	-1	-1	-1	1
25	26	0	0	0	0	-2
29	27	0	0	0	0	0
19	28	0	-2	0	0	0
10	29	1	-1	-1	1	1
8	30	1	1	1	-1	-1
21	31	0	0	-2	0	0
5	32	-1	-1	1	-1	-1

Table 2: Limits of the oil palm stripping machine operational parameters.

No.	Factor Description	Factor Symbols	Factor Values	
		Actual	Low	High
1	Rotary speed of machine (rpm)	*N*	200	500
2	Mass of palm fruit (kg)	*m*	15	35
3	Length of stripping shaft(mm)	*L*	1200	2500
4	Number of beaters	B	10	25
5	Stripping time (s)	*T*	180	420

tors and the operational variables of the machine using MINITAB. The main effects plots, model adequacy measures and residual diagnostic plots displayed by the software along with the fitted linear models was used to evaluate if the functions approximated the true responses adequately, after which non linear model was found appropriate. The generated data allowed analysis of non-linear interactions of the initial linear designs and was used to develop nonlinear models for the machine responses (Equation 5) [20].

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j<} \sum_{j=2}^{k} \beta_{ij} x_i x_j \tag{5}$$

Where "Y" is the predicted response; $\beta_{0,}$ the constant (intercept); β_{i}, the linear coefficient and β_{ij}, the cross product coefficient. x_{i} and x_{j} are the independent variables.

For the statistical verification of the fitted functions, model adequacy measures which included model coefficients regression analysis, analysis of variance and lack-of-fit tests were used. The coefficient of determination, R^2 and adjusted coefficient of determination, $adj - R^2$ for each of the developed models was determined so as to know how properly the models fit the measured data. The values of R^2 lies between the zero and one ($i.e$ 0% $\leq R^2 \leq$ 100%) and as the value of R^2 approaches one, the better the fits of the estimated model

Then analysis of variance was employed in testing the adequacy of the fitted models to be true approximations of the measured data with $\alpha \ \leq 0.05$..

The Adopting the same procedure factor levels determination, confirmation tests were conducted . Point prediction capability of MINITAB was exploited while predicting the performance indicators (stripping efficiency (η), Throughput capacity (TP) and Specific energy consumption (SE)) of the machine on the bases of factor combinations of the confirmation experimental plan. Upon the models validations, optimal settings of the response indicators and factors were determined and multiple response optimization models were formulated using non linear mathematical programming approach.

The actual power consumption of the machine transmitted by the motor during operation was measured with a clamp wattmeter.

3. Results and discussion

3.1. Modeling of stripping machine

The factor limits determined were shown in Table 2.

Operating the machine at the factor settings (design layout) with length of shaft rounded up to the nearest significant whole number gave the responses as shown Table 3.

From Table 3 the quadratic models were developed as shown in Equations 6 – 8.

Table 3: Performance Responses of the Machine.

Run Order	Natural values of Factors					Responses		
	N	m	L	B	T	η	TP	SE
1	350	25	1850	17.5	300	85.5	26.3	64.7
2	500	15	2500	10	420	90.1	14	75.6
3	200	35	2500	25	180	77.3	28	61
4	350	45	1850	17.5	300	81.13	32.2	58.89
5	200	35	2500	10	420	66.2	32	65
6	350	25	1850	17.5	300	85.5	26.4	64.72
7	350	25	3150	17.5	300	80.2	23.7	68.5
8	350	25	1850	32.5	300	91	23.2	65.5
9	50	25	1850	17.5	300	48	18.2	60
10	200	35	1200	10	180	14.5	6.8	43
11	350	25	1850	17.5	300	85.5	26.3	64.72
12	650	25	1850	17.5	300	55.7	14.7	69
13	500	15	1200	10	180	30	10.5	65.85
14	350	25	1850	17.5	540	87	27.7	70.5
15	500	35	2500	25	420	75.3	33.9	71.31
16	350	25	1850	17.5	300	85.5	26.3	65
17	200	15	2500	25	420	77.87	15	71.57
18	350	25	1850	2.5	300	56.5	12.4	63.3
19	500	35	1200	25	180	78.57	23.6	61
20	350	25	1850	17.5	300	85.5	26.2	65
21	200	15	1200	25	180	77.2	9.5	50
22	500	15	2500	25	180	53	10.2	58.3
23	200	35	1200	25	420	73	30.5	62.31
24	500	35	1200	10	420	72	21.4	65.56
25	200	15	1200	10	420	55.2	11.5	66.71
26	350	25	1850	17.5	60	54.3	13	47
27	350	25	1850	17.5	300	85.5	26.3	65
28	350	5	1850	17.5	300	89.3	8.7	70
29	500	15	1200	25	420	88	8.9	72
30	500	35	2500	10	180	58.9	8.5	52
31	350	25	550	17.5	300	58.6	16.5	60
32	200	15	2500	10	180	75.2	10.9	65.46

Analysis of variance for the nonlinear models were conducted and the values of $F_{tab(model)}$,$F_{tab(linear)}$, $F_{tab(square)}$, $F_{tab(interaction)}$ and F_{tabLOF} were determined as 2.71, 5.05, 5.05, 3.33 and 4.95 respectively. It was observed from the ANOVA that $F_{\mathrm{cal}} > F_{\mathrm{tab}}$ for all responses. The models for stripping efficiency, throughput capacity and specific energy was best described by a nonlinear models, Equations 6, 7 and 8 (expressed in their natural Terms) were gotten after eliminating the insignificant factors in the model terms while maintaining hierarchy of the model equation using the stepwise elimination method.

$$\eta = 85.4900 + 1.8667\ \mathrm{N} - 1.9642\ \mathrm{m} + 5.3583\ \mathrm{L} + 8.6308\ \mathrm{B} + 8.2667\ \mathrm{T} - 8.4025\ \mathrm{N}^2 - 0.0613\ \mathrm{m}^2 - 4.0150\ \mathrm{L}^2 - 2.9275\ \mathrm{B}^2 - 3.7025\ \mathrm{T}^2 + 4.8838\ \mathrm{Nm} - 4.2463\ \mathrm{NL} - 3.1500\ \mathrm{NB} + 4.8037\ \mathrm{NT} - 0.3838\ \mathrm{mL} + 2.9375\ \mathrm{mB} - 1.1587\ \mathrm{mT} - 9.5000\ \mathrm{LB} - 2.6788\ \mathrm{LT} - 4.8000\ \mathrm{BT} \ (6)$$

$$\mathrm{TP} = 26.3023 - 0.8417\ \mathrm{N} + 5.8833\ \mathrm{m} + 1.8417\ \mathrm{L} + 2.7333\ \mathrm{B} + 3.6917\ \mathrm{T} - 2.4648\mathrm{N}^2 - 1.4648\ \mathrm{m}^2 - 1.5523\ \mathrm{L}^2 - 2.1273\ \mathrm{B}^2 - 1.4898\ \mathrm{T}^2 - 0.4125\ \mathrm{Nm} - 1.5875\ \mathrm{NL} - 0.5250\ \mathrm{NT} + 0.6500\ \mathrm{mL} + 3.1625\ \mathrm{mB} + 2.6625\ \mathrm{mT} - 0.0375\ \mathrm{LB} + 0.9625\ \mathrm{LT} - 1.5750\ \mathrm{BT} \ (7)$$

$$\mathrm{SE} = 64.8485 + 2.2738\ \mathrm{N} - 2.7721\ \mathrm{m} + 2.1171\ \mathrm{L} + 0.5296\ \mathrm{B} + 5.8521\ \mathrm{T} - 0.0810\ \mathrm{N}^2 - 0.0948\ \mathrm{m}^2 - 0.1435\ \mathrm{L}^2 - 0.1060\ \mathrm{B}^2 - 1.5185\ \mathrm{T}^2 - 3.0131\ \mathrm{NL} - 0.0694\ \mathrm{NB} + 0.0744\ \mathrm{NT} + 0.0669\ \mathrm{mL} + 3.2381\ \mathrm{mB} + 0.0569\ \mathrm{mT} \ (8)$$

Table 4: Coefficient of determination and error standard deviation of the nonlinear models.

Responses	S	R-sq	R-sq(adj)	R-sq(pred)
η	0.150678	100.00%	99.99%	99.94%
TP	0.0810995	100.00%	99.99%	99.94%
SE	0.117344	99.99%	99.97%	99.95%

The model individual terms are said to be statistically insignificant to the responses if the P- value is greater than 0.05. The coefficient of determination and error standard deviation of the nonlinear models were shown in Table 4.

Evident from the Table 4, the nonlinear models fit the data properly because the values of *"R^2"* and *"adj- R^2"* increased while the value of *"S"* reduced in each model and hence it can be deduced that the interaction and square terms improved the adequacy of the models. The introduction of the quadratic terms improved the adequacy of the models

Employing a multi objective multi -factor optimization technique [10] that optimizes a set of responses and defines the best factor settings for a solution of objective function; the developed model were subjected to optimization The objective was to minimize specific energy consumption (Equation 8) and maximize stripping efficiency (Equation 6) while setting a target for the throughput capacity (Equation 7) and the total sum of the factors. It is evident from Table 3 that maximum experimental values of the stripping efficiency and throughput are 89.3% and 33.9 kg/h respectively. These two performance indicators are desired not to be less than the above maximum values; therefore, targets were defined on both responses based on these conditions. In addition, a bound of five (5) was defined on the total sum of the high level of factors investigated as linear inequality constraints required in optimization of this nature. Also as part of linear inequality constraints required, bounds based factor levels was placed on individual factors. The high level of each factor and the total sum of the five factors at this level cannot exceed five. Therefore, a nonlinear mathematical programming model for the optimization of the stripping machine was formulated in natural term thus:

Minimize:

$$\mathrm{SE} = 64.8485 + 2.2738\ \mathrm{N} - 2.7721\ \mathrm{m} + 2.1171\ \mathrm{L} + 0.5296\ \mathrm{B} + 5.8521\ \mathrm{T} - 0.0810\ \mathrm{N}^2 - 0.0948\ \mathrm{m}^2 - 0.1435\ \mathrm{L}^2 - 0.1060\ \mathrm{B}^2 - 1.5185\ \mathrm{T}^2 - 3.0131\ \mathrm{NL} - 0.0694\ \mathrm{NB} + 0.0744\ \mathrm{NT} + 0.0669\ \mathrm{mL} + 3.2381\ \mathrm{mB} + 0.0569\ \mathrm{mT}$$

Subject to:

Non linear inequality constraints:

$$\eta = 85.4900 + 1.8667\ \mathrm{N} - 1.9642\ \mathrm{m} + 5.3583\ \mathrm{L} + 8.6308\ \mathrm{B} + 8.2667\ \mathrm{T} - 8.4025\ \mathrm{N}^2 - 0.0613\ \mathrm{m}^2 - 4.0150\ \mathrm{L}^2 - 2.9275\ \mathrm{B}^2 - 3.7025\ \mathrm{T}^2 + 4.8838\ \mathrm{Nm} - 4.2463\ \mathrm{NL} - 3.1500\ \mathrm{NB} + 4.8037\ \mathrm{NT} - 0.3838\ \mathrm{mL} + 2.9375\ \mathrm{mB} - 1.1587\ \mathrm{mT} - 9.5000\ \mathrm{LB} - 2.6788\ \mathrm{LT} - 4.8000\ \mathrm{BT}$$

$$\mathrm{TP} = 26.3023 - 0.8417\ \mathrm{N} + 5.8833\ \mathrm{m} + 1.8417\ \mathrm{L} + 2.7333\ \mathrm{B} + 3.6917\ \mathrm{T} - 2.4648\mathrm{N}^2 - 1.4648\ \mathrm{m}^2 - 1.5523\ \mathrm{L}^2 - 2.1273\ \mathrm{B}^2 - 1.4898\ \mathrm{T}^2 - 0.4125\ \mathrm{Nm} - 1.5875\ \mathrm{NL} - 0.5250\ \mathrm{NT} + 0.6500\ \mathrm{mL} + 3.1625\ \mathrm{mB} + 2.6625\ \mathrm{mT} - 0.0375\ \mathrm{LB} + 0.9625\ \mathrm{LT} - 1.5750\ \mathrm{BT}$$

Linear inequality constraints:

$$N + m + L + B + T \leq 5$$

$$Low\ value \leq variables \leq High\ value$$

Substituting maximum values of efficiency, throughput and rearranging the constraints in the form of C(x) < 0 suitable for optimisation, we have:

$$3{,}81 - 1.8667\ \mathrm{N} + 1.9642\mathrm{m} - 5.3583\ \mathrm{L} - 8.6308\ \mathrm{B} - 8.2667\ \mathrm{T} + 8.4025\ \mathrm{N}^2 + 0.0613\ \mathrm{m}^2 + 4.0150\ \mathrm{L}^2 + 2.9275\ \mathrm{B}^2 + 3.7025\ \mathrm{T}^2 - 4.8838\ \mathrm{Nm} + 4.2463\mathrm{NL} + 3.1500\ \mathrm{NB} - 4.8037\mathrm{NT} -+ 0.3838\ \mathrm{mL} - 2.9375\ \mathrm{mB} + 1.1587\ \mathrm{mT} + 9.5000\ \mathrm{LB} + 2.6788\ \mathrm{LT} + 4.8000\ \mathrm{BT} < 0$$

$$7.5977 + 0.8417\ \mathrm{N} - 5.8833\ \mathrm{m} - 1.8417\ \mathrm{L} - 2.7333\mathrm{B} - 3.6917\ \mathrm{T} + 2.4648\mathrm{N}^2 + 1.4648\ \mathrm{m}^2 + 1.5523\ \mathrm{L}^2 -+ 2.1273\ \mathrm{B}^2 + 1.4898\ \mathrm{T}^2 + 0.4125\ \mathrm{Nm} + 1.5875\ \mathrm{NL} + 0.5250\ \mathrm{NT} - 0.6500\ \mathrm{mL} - 3.1625\ \mathrm{mB} - 2.6625\ \mathrm{mT} + 0.0375\ \mathrm{LB} - 0.9625\mathrm{LT} + 1.5750\ \mathrm{BT} < 0$$

Application of a Multi-objective Optimization Sequential Quadratic Programming, MOSQP solver to the set of nonlinear system shows that the optimal factor settings required for maximum stripping efficiency and throughput capacity at minimum specific energy consumption is 0.5859, 2.0, 1.1919, -1.2727 and 2.0 corresponding to natural values of 438rpm, 45kg, 2625mm, 8 beaters and 540 seconds for the rotary speed of machine, mass of palm fruit, shaft length, number of beaters and stripping time respectively. The optimal response at these factor settings is 84.2%, 33.7kg/s (≈ 225kg/hr) and 57.51 kJ/kg at an optimality rate of 91%, 99.1% and 97.2% for the stripping efficiency, throughput capacity and specific energy consumption respectively with an overall optimality value of 95%.

3.2. Model validation/confirmatory test results

To confirm the optimal design settings predicted by the optimality test, the machine was modified and operated at the optimal factor settings of 438rpm, 45kg, 2625mm, 8 beaters and 540 seconds for the machine speed, mass of loaded palm bunch, shaft length, number of beaters and stripping time respectively- and five experiments conducted to determine variation in the predicted and actual results of the machine as given in Table 5. It was established that the machine when operated at the optimal settings gave values close to the predicted optimal results at 95% confidence level (± 0.05).

4. Conclusion

An improved oil palm stripping machine was evaluated in this study with the aim of optimizing its performance in stripping oil palm bunches. The operational parameters evaluated were the rotary speed of the machine, mass of loaded oil palm, length of the stripping shaft, number of beaters and stripping time while the stripping efficiency, throughput capacity and specific energy consumption of the machine constituted the responses or performance parameters. Two level half factorial central composite design (CCD) was employed in this regard and nonlinear models were best suited for empirical predictions based on model adequacy measures, analysis of variance (ANOVA) and residual plots. The developed models were used to optimize the performance of the machine using the nonlinear programming approach with the aid of MOSQP solver and it was established that the optimal factor settings of the machine (to the nearest whole number) are 438 rpm, 45 kg, 2625 mm, 8 beaters and 540 seconds for the machine speed, mass of loaded palm bunch, shaft length, number of beaters and stripping time respectively. The optimal responses at these factor settings were 84.2%, 225 kg/hr and 57.51 kJ/kg at an optimality rate of 91%, 99.1% and 97.2% for the stripping efficiency, throughput capacity and specific energy consumption respectively with an overall optimality value of 95%. Also, confirmatory test results showed that the machine when operated at the optimal settings gave values close to the predicted optimal results at 95% confidence level (± 0.05 error margin) hence the models are suitable for better approximation and therefore recommended

Table 5: Model Confirmatory test results.

S.No.	Actual			Predicted			% error		
	η	TP	SE	η	TP	SE	η	TP	SE
1	84.5	34.5	58	84.2	33.7	57.5	0.00355	0.023188	0.008621
2	85.1	34.5	60	84.2	33.7	57.5	0.010576	0.023188	0.041667
3	84.7	34.7	57	84.2	33.7	57.5	0.005903	0.028818	-0.00877
4	85	33.8	57	84.2	33.7	57.5	0.009412	0.002959	-0.00877
5	84.7	34.7	58	84.2	33.7	57.5	0.005903	0.028818	0.008621

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