# Multi-objective optimization for improving cutting efficiency and power energy consumption in chopping agricultural residues using a modified Taguchi approach

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**Abstract**:

This study focuses on optimizing the chopping processes of corn stalks, which are abundant biomass and forage resources. The reduction of shearing force is crucial for energy efficiency and the compact mechanical design of chopping devices. However, high cutting velocities can still lead to substantial power consumption even with low shearing forces. Therefore, the objective is to minimize both cutting force and power consumption simultaneously. The paper proposes an approach to solve this optimization problem using a modified Taguchi design of experiments and Chauvenet's criterion for considering the statistically accepted data from repeated tests. By analysing the variance technique, optimal levels of parameters and their percentage contributions were identified. The results demonstrate the analysis of the modified Taguchi design can effectively address the multi-response optimization problem in chopping corn stalks. The findings have practical implications for the design and operation of chopping machines used for agricultural residues.

**Keywords**: Cutting force; Cutting power; multi-objective optimization; modified Taguchi

## Introduction

Agricultural residues play a crucial role as valuable resources for biomass and animal feed. Prior to producing forage and biomass energy, it is essential to reduce their size. However, this size reduction process has been regarded as highly inefficient in terms of energy consumption. Evaluating the efficiency of size reduction traditionally involves measuring the cutting force and energy expended. Promisingly, equipment utilizing shear mode for size reduction has shown potential for enhancing energy efficiency. For cutting forage stems, the energy required has been extensively studied across various plant species, cutting velocities, moisture contents, and stem sizes. The findings can be categorized into three groups: quasistatic shearing (cutting velocities below 30 mm/s), cutting with a counter-edge (velocities above 0.5 m/s), and impact cutting without a counter-edge (speeds up to 60 m/s). Notably, minimal energy is needed for quasistatic shearing and cutting with a counter-edge. In the case of corn stalks, Prasad and Gupta [1] measured specific energies ranging from 19 to 24 mJ/mm$^2$ in quasistatic conditions. Conversely, the energy required for impact cutting is generally one to two orders of magnitude higher than that for quasistatic or counter-edge cutting.

Numerous studies have utilized quasistatic tests to examine cutting force and cutting energy in various agricultural residues. A universal machine to investigate the impact of grape cane diameter and age on cutting force and energy. Using the same experimental setup, researchers evaluated the effects of moisture content, internode region, and oblique angle on the mechanical properties of sainfoin stems [2]. Additionally, another study found that the shearing angle exerted a substantial influence on cutting force and specific energy

[3], with smaller cutting angles corresponding to higher cutting resistance. For corn stalks, Prasad and Gupta [1] demonstrated that optimal values of bevel angle, knife approach

angle, and shear angle were 23 degrees, 32 degrees, and 55 degrees, respectively, leading to minimal cutting force and energy consumption. Azadbakht and Zahedi's [4] investigation revealed the significant effects of height, moisture content, and their interaction on cutting energy. They further explored the relationship between moisture content, cutting height, and energy consumption during impact cutting of canola stalks [5].

Reviewing the abovementioned literature, it becomes evident that cutting speed and blade geometry exert substantial influences on cutting force and cutting energy in agricultural residues. While some studies have explored counter-edge cutting under a quasistatic mode with low cutting velocities, it is important to note that high cutting velocities can result in significant power consumption, even with low shearing forces. Consequently, the aim is to minimize both cutting force and power consumption simultaneously. In a recent investigation, factorial experimental designs were employed [6].

The main aims of this study are to provide another approach of solving such problem by using modified Taguchi analysis technique. The modified Taguchi method has been employed in several experimental investigations in agriculture, biotechnology and engineering [7–12].

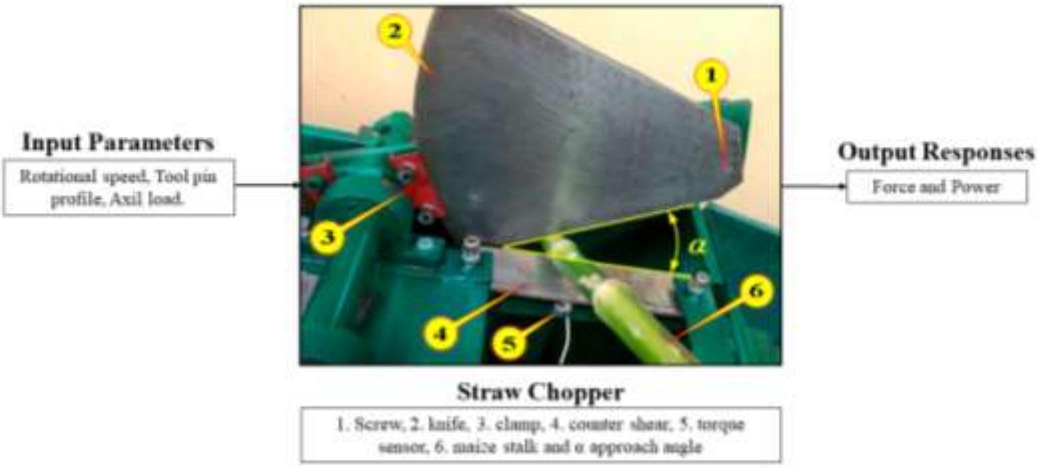

Figure 1 Schematics of experimental setup [13].

## Design of Experiment

In this study, the duration of each cutting pulse is calculated as the time required for a point on the cutting edge to completely pass the stalk diameter. The approach angle, the feed angle and the cutting velocity were selected to be three experimental variables. The design of experiments was built using three parameters at three levels each, leading to the L27 orthogonal array of tests. The investigated parameters and their levels considered in this study are shown in Table 1.

Table 1 Process parameters

| **Parameters** | | **Parameter levels** | | |
|---|---|---|---|---|
| | | **Level-1** | **Level-2** | **Level-3** |
| **Velocity** | V (m/s) | 4.40 | 5.66 | 6.91 |
| **Approach angle** | α ($^o$) | 0 | 30 | 60 |
| **Feeding angle** | β ($^o$) | 0 | 25 | 50 |

As the test data was from the literature Vu et al. [13], which considered 9 test data points and repeated 3 times each which gives the 27 test data points. As the test data was repeated the tendency was irregular that considered for the average test data for process parameters (Force, F and Power, P). As average values (in Table 2 & 3) are considered for the analysis in this study, for the variation in the test data a statistical measure was utilised (viz., standard deviation (SD)) to quantify the amount of the variation in the set of test data points. SD is a tool that aids in understanding data variability, making comparisons, estimating uncertainty, and drawing meaningful conclusions from data sets. It provides valuable insights into the characteristics of the data.

Table 2 Average test and standard deviation (SD) values for Force (Test data from Vu et al. [13])

| **Test No** | **Test 1** | **Test 2** | **Test 3** | **Average** | **SD** |
|---|---|---|---|---|---|
| **1** | 706.07 | 617.68 | 502.1 | 608.62 | 102.29 |
| **2** | 313.99 | 264.13 | 276.6 | 284.91 | 25.95 |

| | | | | | |
|---|---|---|---|---|---|
| **3** | 261.94 | 269.8 | 263.6 | 265.11 | 4.14 |
| **4** | 485.1 | 479.44 | 414.8 | 459.78 | 39.06 |
| **5** | 312.8 | 255.07 | 242.6 | 270.16 | 37.45 |
| **6** | 287.93 | 267.58 | 261.9 | 272.47 | 13.69 |
| **7** | 344.59 | 317.39 | 289.1 | 317.03 | 27.75 |
| **8** | 307.19 | 273.2 | 250.5 | 276.96 | 28.53 |
| **9** | 385.38 | 361.59 | 317.4 | 354.79 | 34.50 |

Table 3 Average test and standard deviation (SD) values for Power (Test data from Vu et al. [13])

| **Test No** | **Test 1** | **Test 2** | **Test 3** | **Average** | **SD** |
|---|---|---|---|---|---|
| **1** | 82.38 | 72.06 | 58.58 | 71.01 | 11.93 |
| **2** | 36.63 | 30.82 | 32.27 | 33.24 | 3.02 |
| **3** | 30.56 | 31.48 | 26.32 | 29.45 | 2.75 |
| **4** | 72.77 | 71.92 | 62.23 | 68.97 | 5.86 |
| **5** | 46.93 | 38.26 | 36.39 | 40.53 | 5.62 |
| **6** | 43.19 | 40.13 | 39.28 | 40.87 | 2.06 |

| | | | | | |
|---|---|---|---|---|---|
| **7** | 63.17 | 58.19 | 52.99 | 58.12 | 5.09 |
| **8** | 56.32 | 50.09 | 45.93 | 50.78 | 5.23 |
| **9** | 70.65 | 66.29 | 58.19 | 65.04 | 34.50 |

Table 4 Modified Taguchi analysis

| **Test No** | **V** | **α** | **β** | **Dummy** | **Force** | **Power** |
|---|---|---|---|---|---|---|
| **1** | 1 | 1 | 1 | d1 | 608.62 | 71.01 |
| **2** | 1 | 2 | 2 | d2 | 284.91 | 33.24 |
| **3** | 1 | 3 | 3 | d3 | 265.11 | 29.45 |
| **4** | 2 | 1 | 2 | d3 | 459.78 | 68.97 |
| **5** | 2 | 2 | 3 | d1 | 270.16 | 40.53 |
| **6** | 2 | 3 | 1 | d2 | 272.47 | 40.87 |
| **7** | 3 | 1 | 3 | d2 | 317.03 | 58.12 |
| **8** | 3 | 2 | 1 | d3 | 276.96 | 50.78 |
| **9** | 3 | 3 | 2 | d1 | 354.79 | 65.04 |

Table 4 presents the levels of process parameters (viz., velocity, V, approach angle, α, feeding angle, β and dummy variable, D) as per the Taguchi's $L_9$ OA and the test data of the performance indicators (viz., Force, F (N) and Power, P (W)) for the nine test runs. Table5 presents analysis of variance (ANOVA) results.

Table 5 Analysis of Variance (ANOVA) for test data and standard deviation (SD)

| **Parameters** | **1-Mean** | **2-Mean** | **3-Mean** | **Sum of Squares (SOS)** | **Contribution (%)** |
|---|---|---|---|---|---|
| **Force, F (N); grand mean = 345.54 N** | | | | | |
| **V** | 386.21 | 334.14 | 316.26 | 7924.83 | 7.27 |
| **α** | 461.81 | 277.34 | 297.46 | 61443.10 | 56.36 |
| **β** | 386.02 | 366.49 | 284.10 | 17557.10 | 16.10 |
| **D** | 411.19 | 291.47 | 333.95 | 22103.14 | 20.27 |
| **SD for force; grand mean = 34.82 N** | | | | | |
| **V** | 44.13 | 30.08 | 30.26 | 389.69 | 6.36 |
| **α** | 56.36 | 30.65 | 17.45 | 2349.48 | 38.32 |
| **β** | 48.17 | 33.16 | 23.13 | 952.87 | 15.54 |
| **D** | 58.09 | 22.48 | 23.90 | 2439.91 | 39.79 |
| **Power, P (W); grand mean = 50.89 W** | | | | | |
| **V** | 44.57 | 50.12 | 57.98 | 272.53 | 13.88 |
| **α** | 66.03 | 41.52 | 45.12 | 1051.34 | 53.55 |
| **β** | 54.22 | 55.75 | 42.70 | 305.43 | 15.56 |
| **D** | 58.86 | 44.07 | 49.74 | 333.86 | 17.01 |
| **SD for power; grand mean = 5.32 W** | | | | | |
| **V** | 5.90 | 4.51 | 5.55 | 3.13 | 4.63 |
| **α** | 7.63 | 4.63 | 3.71 | 25.17 | 37.19 |
| **β** | 6.41 | 5.07 | 4.49 | 5.80 | 8.57 |
| **D** | 7.96 | 3.39 | 4.61 | 33.57 | 49.61 |

In the Taguchi approach, every test run involves a combination of various levels of input process parameters. This allows us to analyse the impact of independent input process parameters on the output responses. To achieve this, we first sum up the output response values corresponding to each level setting of the process parameter and calculate the mean. To further investigate the sensitivity of the output response to changes in the input process parameter levels, we evaluate the sum of the squares (SOS) of the deviation of each mean value from the grand mean for the process parameters. This helps us determine the % contribution of each process parameter by dividing the respective SOS by the total SOS of the test runs.

**Modified Taguchi's analysis**

It is seen that percentage contribution of velocity, approach angle, feeding angle and the dummy variable on the force are 7.27 %, 56.36%, 16.10% and 20.27 % respectively; standard deviation for force are 6.36 %, 38.32 %, 15.54 % and 39.79 % respectively; power are 13.88 %, 53.55 %, 15.56 % and 17.01 % respectively; and standard deviation for power are 4.63 %, 37.19 %, 8.57 % and 49.61 % respectively. The percentage contribution of the dummy variable on the force, SD for force, power and SD for power are 20.27 %, 39.79 %, 17.01 % and 49.61 % respectively, which are nothing but the error (%).

Additive law [14] provides the estimates of performance indicators from the mean values of ANOVA presented in Table-5. The evaluation procedure for the estimates of the performance indicators explained below. Let $\psi$ be the performance response and $\hat{\psi}$ is its estimate for the process parameters $(V_i, \alpha_j, \beta_k, D_l)$ varying the subscripts $i, j, k, l$ from 1 to 3. Designating $\psi(V_i)$, $\psi(\alpha_j)$, $\psi(\beta_k)$ and $\psi(D_l)$ as mean values of $\psi$ corresponding to the $i^{th}$ level of $V_,$ $j^{th}$ level of $\alpha$, $k^{th}$ level of $\beta$ and $l^{th}$ level of D. The grand mean of $\psi$ is designated by $\psi_{mean}$for the 9 test runs. Following the additive law, estimate $\hat{\psi}$ for the specified $(V_i, \alpha_j, \beta_k, D_l)$ is:

$$\hat{\psi} = \psi(V_i, \alpha_j, \beta_k, D_l) = \psi(V_i) + \psi(\alpha_j) + \psi(\beta_k) + \psi(D_l) - 3 \times \psi_{mean} \text{(Equation 1)}$$

For the specified $(V_i, \alpha_j, \beta_k)$, equation (11) reduces to

$$\hat{\psi} = \psi(V_i, \alpha_j, \beta_k) = (V_i) + \psi(\alpha_j) + \psi(\beta_k) - 2 \times \psi_{mean} \quad \text{(Equation 1)}$$

Estimates from equations (1) and (2) provide different $\psi$ values, whose deviation is $\psi(D_l) - \psi_{mean}$. Three deviations can be found for the three levels ($l$ =1, 2, 3). Superimposing the minimum and maximum deviation values to the estimates using equation (2), the range of estimates is arrived. Table 6 presents the estimates of performance responses. Test data (Vu et al. [13]) of performance indicators are within/close to the estimated range. Figure 2 present the estimates of the performance indicators including test data (Vu et al. [13]) for all possible 27 combinations $((((V_i, \alpha_j, \beta_k), k = 1,2,3), j = 1,2,3), i = 1,2,3)$ of process parameters.

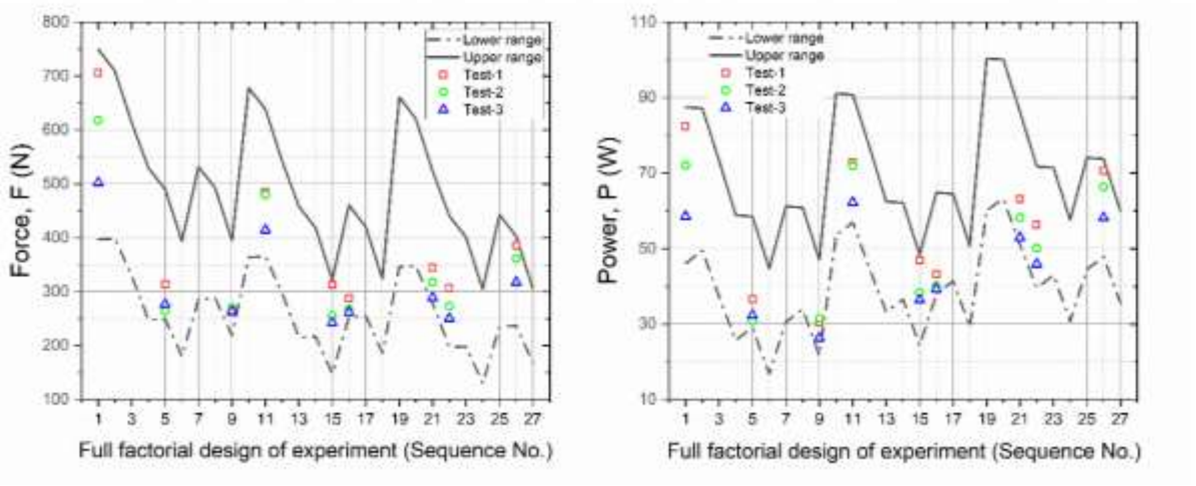

Figure 2 Estimates of the test data.

Empirical relations (Equations 3 and 4) are developed for the force and power in terms of V, α and β using the additive law from the mean values of ANOVA presented in Table-6 in the form:

$$\text{Force} = 286.90 - 34.9761\xi_1 + 17.10\xi_1^2 - 82.175\xi_2 + 102.29\xi_2^2 - 50.9589\xi_3 - 31.43\xi_3^2$$

(Equation 3)

$$\text{Power} = 49.13 + 6.706667\xi_1 - 1.15\xi_1^2 - 10.4556\xi_2 + 14.06\xi_2^2 - 5.75944\xi_3 - 7.29\xi_3^2$$

(Equation 4)

Here,

$$\xi_1 = \frac{V-5.66}{1.26},\ \xi_2 = \frac{\alpha-30}{30}\ and\ \xi_3 = \frac{\beta-25}{25}$$

Table 6 Estimates of Performance Responses

| **Test Run** | **Levels of process Parameters** | | | | **Test Data**[13] | **Eq.(2) ($n_p$=3)** | **RE (%)** | **Eq.(1) ($n_p$=4)** | **Range of estimates** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | V | α | β | D | | | | | From | To |
| | | | | | **Force, F (N)** | | | | | |
| **1** | 1 | 1 | 1 | 1 | 608.62 | 542.96 | 10.8 | 608.62 | 542.87 | 543.13 |
| **2** | 1 | 2 | 2 | 2 | 284.91 | 338.97 | - | 284.91 | 338.88 | 339.14 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 19.0 | | | |
| **3** | 1 | 3 | 3 | 3 | 265.11 | 276.70 | -4.4 | 265.11 | 276.60 | 276.86 |
| **4** | 2 | 1 | 2 | 3 | 459.78 | 471.36 | -2.5 | 459.78 | 471.27 | 471.53 |
| **5** | 2 | 2 | 3 | 1 | 270.16 | 204.50 | 24.3 | 270.16 | 204.41 | 204.67 |
| **6** | 2 | 3 | 1 | 2 | 272.47 | 326.54 | -19.8 | 272.47 | 326.44 | 326.70 |
| **7** | 3 | 1 | 3 | 2 | 317.03 | 371.09 | -17.1 | 317.03 | 371.00 | 371.26 |
| **8** | 3 | 2 | 1 | 3 | 276.96 | 288.55 | -4.2 | 276.96 | 288.45 | 288.71 |
| **9** | 3 | 3 | 2 | 1 | 354.79 | 289.14 | 18.5 | 354.79 | 289.04 | 289.30 |
| **Power, P (W);** | | | | | | | | | | |
| **1** | 1 | 1 | 1 | 1 | 71.01 | 63.04 | 11.2 | 71.01 | 62.94 | 63.20 |
| **2** | 1 | 2 | 2 | 2 | 33.24 | 40.06 | -20.5 | 33.24 | 39.96 | 40.22 |
| **3** | 1 | 3 | 3 | 3 | 29.45 | 30.61 | -3.9 | 29.45 | 30.51 | 30.77 |
| **4** | 2 | 1 | 2 | 3 | 68.97 | 70.13 | -1.7 | 68.97 | 70.03 | 70.29 |
| **5** | 2 | 2 | 3 | 1 | 40.53 | 32.56 | 19.7 | 40.53 | 32.46 | 32.72 |
| **6** | 2 | 3 | 1 | 2 | 40.87 | 47.68 | -16.7 | 40.87 | 47.58 | 47.84 |
| **7** | 3 | 1 | 3 | 2 | 58.12 | 64.93 | -11.7 | 58.12 | 64.83 | 65.09 |
| **8** | 3 | 2 | 1 | 3 | 50.78 | 51.93 | -2.3 | 50.78 | 51.84 | 52.10 |
| **9** | 3 | 3 | 2 | 1 | 65.04 | 57.07 | 12.3 | 65.04 | 56.98 | 57.24 |

The above modified Taguchi method is modified by introducing the Chauvenet’s criterion to trace and discard the statistically unacceptable values from the data of repeated experiments for each test run and the fictitious process parameters, without enhancing the test runs and estimating the expected range of the output response for the full factorial design of experiments. The 1.38 value in equation 5 can be taken for the 3 repeated test as per the chauvent’s criterion . The predictions for the output responses (viz., Force and Power) by utilising the lower range ($\bar{x}$) and lower SD ($\sigma$) which indicates lower and upper estimates of test data by using equation 3. The predictions of the SD are to be the final estimates for the entire test data of force (see table 7) and power (see table 8) which also indicates the predominant estimation of the process parameter which can help in optimising the parameters and gives the appropriate estimation of the data.

$$\bar{x} - 1.38\sigma \text{ Equation 5}$$

Table 7 Mean values of Taguchi optimisation, standard deviation (SD) with the range for Force (F) and Estimates for test data.

| **Sno.** | **F (Eq.2)** | **Range (x̄)** | | **F (SD) (Eq.2)** | **SD Range (σ)** | | **Estimate (Eq.3)** | |
|---|---|---|---|---|---|---|---|---|
| | | Lower | Upper | | Lower | Upper | Lower | Upper |
| **1** | 542.95 | 488.86 | 608.62 | 79.02 | 66.67 | 102.29 | 396.85 | 749.78 |
| **2** | 523.45 | 469.36 | 589.12 | 64.01 | 51.66 | 87.28 | 398.07 | 709.56 |
| **3** | 441.06 | 386.97 | 506.72 | 53.98 | 41.63 | 77.25 | 329.51 | 613.33 |
| **4** | 358.50 | 304.41 | 424.17 | 53.31 | 40.96 | 76.58 | 247.88 | 529.85 |
| **5** | 339.00 | 284.91 | 404.67 | 38.30 | 25.95 | 61.57 | 249.10 | 489.63 |
| **6** | 256.60 | 202.51 | 322.27 | 28.27 | 15.92 | 51.54 | 180.54 | 393.40 |
| **7** | 378.58 | 324.49 | 444.25 | 40.11 | 27.76 | 63.38 | 286.18 | 531.71 |
| **8** | 359.08 | 304.99 | 424.75 | 25.09 | 12.75 | 48.36 | 287.40 | 491.49 |
| **9** | 276.68 | 222.59 | 342.35 | 15.07 | 2.72 | 38.34 | 218.84 | 395.26 |
| **10** | 490.86 | 436.77 | 556.53 | 64.97 | 52.62 | 88.24 | 364.15 | 678.30 |
| **11** | 471.36 | 417.27 | 537.03 | 49.95 | 37.61 | 73.23 | 365.37 | 638.08 |
| **12** | 388.97 | 334.88 | 454.63 | 39.93 | 27.58 | 63.20 | 296.81 | 541.85 |
| **13** | 306.41 | 252.32 | 372.08 | 39.26 | 26.91 | 62.53 | 215.18 | 458.37 |
| **14** | 286.91 | 232.82 | 352.58 | 24.24 | 11.90 | 47.52 | 216.40 | 418.15 |
| **15** | 204.51 | 150.42 | 270.18 | 14.22 | 1.87 | 37.49 | 147.84 | 321.92 |
| **16** | 326.49 | 272.40 | 392.16 | 26.06 | 13.71 | 49.33 | 253.48 | 460.23 |
| **17** | 306.99 | 252.90 | 372.66 | 11.04 | -1.30 | 34.31 | 254.70 | 420.01 |
| **18** | 224.59 | 170.50 | 290.26 | 1.02 | -11.33 | 24.29 | 186.14 | 323.78 |
| **19** | 473.00 | 418.91 | 538.66 | 65.15 | 52.81 | 88.43 | 346.03 | 660.69 |
| **20** | 453.50 | 399.41 | 519.16 | 50.14 | 37.80 | 73.41 | 347.25 | 620.47 |
| **21** | 371.10 | 317.01 | 436.77 | 40.12 | 27.77 | 63.39 | 278.69 | 524.24 |
| **22** | 288.54 | 234.45 | 354.21 | 39.44 | 27.10 | 62.72 | 197.06 | 440.76 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **23** | 269.04 | 214.95 | 334.71 | 24.43 | 12.09 | 47.70 | 198.28 | 400.54 |
| **24** | 186.65 | 132.56 | 252.31 | 14.41 | 2.06 | 37.68 | 129.71 | 304.31 |
| **25** | 308.62 | 254.53 | 374.29 | 26.24 | 13.90 | 49.51 | 235.36 | 442.62 |
| **26** | 289.12 | 235.03 | 354.79 | 11.23 | -1.12 | 34.50 | 236.57 | 402.40 |
| **27** | 206.73 | 152.64 | 272.39 | 1.20 | -11.14 | 24.47 | 168.01 | 306.17 |

Table 8 Mean values of Taguchi optimisation, standard deviation (SD) with the range for Power (P) and Estimates for test data.

| **Sno.** | **P (Eq.2)** | **Range ($\bar{x}$)** | | **P (SD) (Eq.2)** | **Range (σ)** | | **Estimate (Eq.3)** | |
|---|---|---|---|---|---|---|---|---|
| | | Lower | Upper | | Lower | Upper | Lower | Lower |
| **1** | 63.04 | 56.23 | 71.01 | 9.29 | 7.36 | 11.93 | 46.07 | 87.47 |
| **2** | 64.57 | 57.76 | 72.54 | 7.96 | 6.03 | 10.60 | 49.44 | 87.16 |
| **3** | 51.52 | 44.71 | 59.49 | 7.37 | 5.44 | 10.01 | 37.20 | 73.31 |
| **4** | 38.52 | 31.71 | 46.49 | 6.29 | 4.36 | 8.93 | 25.69 | 58.82 |
| **5** | 40.05 | 33.24 | 48.02 | 4.96 | 3.03 | 7.60 | 29.06 | 58.51 |
| **6** | 27.00 | 20.19 | 34.97 | 4.37 | 2.44 | 7.01 | 16.82 | 44.65 |
| **7** | 42.13 | 35.31 | 50.10 | 5.38 | 3.45 | 8.02 | 30.56 | 61.16 |
| **8** | 43.66 | 36.84 | 51.63 | 4.04 | 2.11 | 6.68 | 33.93 | 60.85 |
| **9** | 30.61 | 23.79 | 38.58 | 3.46 | 1.53 | 6.10 | 21.69 | 46.99 |
| **10** | 68.60 | 61.78 | 76.57 | 7.90 | 5.97 | 10.54 | 53.54 | 91.11 |
| **11** | 70.13 | 63.31 | 78.10 | 6.57 | 4.64 | 9.21 | 56.91 | 90.80 |
| **12** | 57.08 | 50.26 | 65.05 | 5.98 | 4.05 | 8.62 | 44.67 | 76.94 |
| **13** | 44.08 | 37.27 | 52.05 | 4.90 | 2.97 | 7.54 | 33.17 | 62.45 |
| **14** | 45.61 | 38.80 | 53.58 | 3.57 | 1.64 | 6.21 | 36.54 | 62.14 |
| **15** | 32.56 | 25.75 | 40.53 | 2.98 | 1.05 | 5.62 | 24.30 | 48.29 |
| **16** | 47.68 | 40.87 | 55.65 | 3.99 | 2.06 | 6.63 | 38.03 | 64.80 |
| **17** | 49.21 | 42.40 | 57.18 | 2.65 | 0.72 | 5.29 | 41.40 | 64.49 |
| **18** | 36.16 | 29.35 | 44.13 | 2.07 | 0.14 | 4.71 | 29.16 | 50.63 |
| **19** | 76.45 | 69.64 | 84.42 | 8.94 | 7.01 | 11.58 | 59.97 | 100.40 |
| **20** | 77.98 | 71.17 | 85.95 | 7.61 | 5.68 | 10.24 | 63.34 | 100.09 |
| **21** | 64.93 | 58.12 | 72.90 | 7.02 | 5.09 | 9.66 | 51.10 | 86.23 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **22** | 51.94 | 45.12 | 59.91 | 5.94 | 4.01 | 8.58 | 39.59 | 71.74 |
| **23** | 53.47 | 46.65 | 61.44 | 4.61 | 2.67 | 7.24 | 42.96 | 71.43 |
| **24** | 40.42 | 33.60 | 48.39 | 4.02 | 2.09 | 6.66 | 30.72 | 57.57 |
| **25** | 55.54 | 48.73 | 63.51 | 5.02 | 3.09 | 7.66 | 44.46 | 74.08 |
| **26** | 57.07 | 50.26 | 65.04 | 3.69 | 1.76 | 6.33 | 47.83 | 73.78 |
| **27** | 44.02 | 37.21 | 51.99 | 3.11 | 1.18 | 5.74 | 35.58 | 59.92 |

## Multi-Objective Optimization

From ANOVA data presented in Table 5, the optimal process parameters to achieve minimum force and minimum power are $V_3\alpha_2\beta_3D_2$ and $V_2\alpha_2\beta_3D_2$ respectively, whereas subscripts denote the levels of the process parameters. To identify a set of optimal process parameters, we employ a straightforward and dependable multi-objective optimization technique [15,16]. This technique involves constructing a multi-objective function ($\zeta$) (Equation 4), which considers force and power. These parameters are normalized based on their minimum values. Introducing the weighing factors $\omega_1(\geq 0)$, $\omega_2(\geq 0)$and $\omega_3(\geq 0)$ which satisfy $\omega_1 + \omega_2 + \omega_3 = 1$. The single objective function ($\zeta$)is constructed in the form

$$\zeta = \omega_1\zeta_1 + \omega_2\zeta_2 = \omega_1\left[\frac{F}{F_{max}}\right] + \omega_2\left[\frac{P}{P_{max}}\right] \text{ (Equation 4)}$$

Minimization of $\zeta$ provides minimum surface roughness and maximum relative density as well as hardness. For common optimal process conditions, $\omega_1 = \omega_2 = \frac{1}{2}$ (equal weighing) is considered in Table 9 and performed ANOVA on values of $\zeta$. The set of optimal process parameters for the minimum $\zeta$ selected are $V_1\alpha_2\beta_3$, which correspond to the velocity, V = 4.4 m/s, approach angle, $\alpha = 30^{o}$ and feeding angle, $\beta = 50^{o}$. Table 10 gives the test results as well as estimates of the performance indicators for the identified optimal process parameters by using empirical relation equation 3 and 4 for force and power respectively.

Table 9 Multi objective optimization function ($\zeta$) equation 4 with equal weighing factors ($\omega 1$ and $\omega 2$) for the Estimated data of force and power in Table-6

| **Sno.** | **Output responses** | | $\zeta_1$ | $\zeta_2$ | **Single objective function** |
|---|---|---|---|---|---|
| | Force | Power | | | |
| **1** | 608.62 | 71.01 | 1.000 | 0.826 | 0.913 |
| **2** | 284.91 | 33.24 | 0.468 | 0.387 | 0.427 |
| **3** | 265.11 | 29.45 | 0.436 | 0.343 | 0.389 |
| **4** | 459.78 | 68.97 | 0.755 | 0.802 | 0.779 |
| **5** | 270.16 | 40.53 | 0.444 | 0.471 | 0.458 |
| **6** | 272.47 | 40.87 | 0.448 | 0.475 | 0.462 |
| **7** | 317.03 | 58.12 | 0.521 | 0.676 | 0.599 |
| **8** | 276.96 | 50.78 | 0.455 | 0.591 | 0.523 |
| **9** | 354.79 | 65.04 | 0.583 | 0.757 | 0.670 |

**ANOVA on $\zeta$**

| **Parameters** | | 1-Mean | 2-Mean | 3-Mean |
|---|---|---|---|---|
| **Velocity** | V (m/s) | **0.58** | 0.57 | 0.60 |
| **Approach angle** | $\alpha$ ($^o$) | 0.76 | **0.47** | 0.51 |
| **Feeding angle** | $\beta$ ($^o$) | 0.63 | 0.63 | **0.48** |

Assuming each performance indicator as a single objective function, optimal set of input variables were obtained from ANOVA (see Table 5) and the single objective functions considered are minimum force and minimum power.

Table 10 Performance indicators for the identified optimal process parameters (viz., velocity, $V = 4.4$ m/s, approach angle, $\alpha = 30^o$ and feeding angle, $\beta = 50^o$)

| **Optimal Solution** | **Force, F (N)** | **Power, P (W)** |
|---|---|---|
| **Experimental** | 251.7 | 26.2 |
| **Estimates (Eq. 3 & 4)** | 256.6 | 27 |

| | | |
|---|---|---|
| **Range of estimates** | 180.54 – 393.40 | 16.82 – 44.65 |

## Results and Discussion

An ANOVA was executed to detect the impact of individual factors. The ANOVA-derived percentage of contribution provides an estimation of the significance of each parameter concerning performance responses. The findings of the ANOVA, along with the contribution of each factor, are illustrated.

In conclusion, this study presents a comprehensive investigation into optimizing the chopping processes of corn stalks, an abundant and valuable source of biomass and forage resources. The research aimed to minimize both cutting force and power consumption simultaneously to enhance energy efficiency and promote compact mechanical designs for chopping devices. By employing a modified Taguchi design of experiments and utilizing standard deviation (SD) and Chauvenet's criterion for repeated tests, the study successfully identified the optimal levels of parameters and their respective percentage contributions.

The results clearly demonstrate the effectiveness of the modified Taguchi design in addressing the multi-response optimization problem related to chopping corn stalks. This approach offers practical implications for the design and operation of chopping machines used in handling agricultural residues.

By reducing shearing forces and power consumption, the proposed optimization technique not only contributes to energy conservation but also offers economic benefits by potentially reducing operational costs for farmers and agricultural industries. Moreover, the findings from this study can pave the way for more sustainable and efficient agricultural practices by maximizing the utilization of corn stalks as a valuable resource.

Overall, this research represents a significant step forward in the development of advanced chopping technologies, which can have far-reaching positive impacts on the agricultural sector, sustainability efforts, and the overall management of biomass resources.

As the demand for renewable energy and environmentally friendly practices continues to grow, the insights gained from this study hold great promise for shaping the future of biomass processing and utilization in the agricultural sector.

## Conclusion

In conclusion, the chopping of agricultural residues, particularly corn stalks, presents a multi-response challenge. It has been observed that increasing the chopping velocity can lead to a decrease in cutting force. However, it is crucial to note that this higher velocity also results in elevated power consumption.

To address this multi-response problem and determine the optimal parameters, a modified Taguchi's analysis and a multi-objective optimisation has been employed. This analytical approach enables us to identify the most efficient settings for achieving minimal cutting force and cutting power simultaneously.

By optimizing these parameters, we can achieved minimum of both the cutting force and cutting power, ensuring the most efficient and sustainable chopping of corn stalks. This finding holds significant potential for enhancing the efficiency and sustainability of agricultural residue management systems. Implementing these insights could lead to more effective and eco-friendly practices in handling corn stalks and other agricultural residues.

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