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Effect of process parameters on the rheological properties of banana *(Musa acuminata)* fiber and optimization using response surface methodology

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ABSTRACT

The labor-intensive, time-consuming, and uneconomical nature of manually extracting banana ***(Musa acuminata)*** fibers from pseudo-stem sheaths has prompted the exploration of automation as a solution. This study focuses on automating the feeding process of banana pseudostem sheaths using a quick return mechanism, which is more effective than other approaches. A comprehensive study was conducted to assess the impact of key process parameters, namely the decorticator (480–540 rpm), roller speed (50–80 rpm), and clearance between rollers (2–4 mm), on the mechanical properties of the extracted banana fiber. The Response Surface Methodology (RSM) was employed for the experimental design and analysis of data, and the mechanical properties under investigation included the tensile strength, Young's modulus, and strain percentage of the banana fiber. The results revealed that the decorticator speed, roller speed, and clearance between rollers are significantly influenced by their mechanical properties. Herein, the optimal process parameter values are identified as follows: a decorticator speed of 510 rpm, roller speed of 65 rpm, and clearance of 3 mm between rollers. The mechanical characterization of the optimized banana fiber exhibited impressive properties, with an ultimate tensile strength of 679.48 MPa, Young's modulus of 25.47 GPa, and strain of 3 %. This study demonstrates that automation coupled with systematic parameter optimization can enhance the mechanical attributes of banana fibers. This research not only addresses the challenges of manual extraction, but also advances the understanding of how process parameters affect banana fiber quality, thereby facilitating the utilization of this natural fiber in various industrial applications.

1. Introduction

In the modern era, natural fibers have demonstrated potential as substitutes for synthetic polymers because of their cost-effectiveness, biodegradability, and advantageous properties, including sound absorption, low abrasiveness, and absence of health risks [1]. These fibers are sourced from diverse plant components and categorized accordingly. Presently, developing nations such as India, Malaysia, Indonesia, Thailand, and other Asian countries possess abundant natural fiber resources such as kenaf, rice husk, banana, and bamboo [2,3]. The banana, scientifically known as the Musa species, is the most widely cultivated horticultural fruit worldwide. It carries rich historical significance, intertwined with Indian heritage and culture. India, as per **APEDA**, contributes 26.45 % to global banana production, but exports only 1 % of its yield. From 2022 to 2023, banana exports totaled $176 million (0.36 million metric tons). With a target of reaching $1 billion in exports in five years, India aims to enhance farmer earnings, benefit 25,000 farmers, and generate jobs for 50,000 individuals in the supply chain. The banana pseudo-stem comprises three main components: a central core (approximately 10–15 % of the stem), banana fiber (approximately 1.5–2%), and residual materials left after extracting banana fiber (constituting 80–85 % of the stem) [4,5]**.** These residual materials

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included sap (35–40 %) and scutcher (40–45 %), as outlined in a study by Jawale and Chaudhari [6]. The quality of the fiber within the pseudo-stem allows the production of multiple types of fabrics. These fabrics are employed in crafting some of the finest textiles such as kimonos and saris (see Table 6).

Banana fibers, derived from the pseudostems of banana plants, have gained attention because of their eco-friendly and sustainable nature. With heightened environmental awareness of high alpha cellulose content and low lignin percentage, its demand surges, expanding into the apparel and home-furnishing sectors. Nowadays, researchers prioritize understanding their tensile strength, flexibility, and durability for diverse applications, such as textiles and composites. This research aims to develop an automated feeding mechanism for banana pseudostem sheaths to enhance efficiency, safety, and economic viability, meeting the demand for sustainable materials [7]. To achieve this, a quick return mechanism was proposed to facilitate the controlled movement of the pseudostem sheaths through the extraction system. A quick return mechanism produces a reciprocating motion, in which the time taken for travel in the return stroke is less than that in the forward stroke. The quick return indicates that the returning stroke is faster than the forward stroke, which helps the tool to retrieve back faster after performing a particular operation; factors such as the decorticator speed, roller speed, and the gap between rollers play pivotal roles in the extraction process and can notably influence the quality of the fiber, and the utilization of Response Surface Methodology (RSM) in this study allows for a systematic exploration of the interaction between process parameters and their effects on banana fiber properties. By employing this experimental design and analysis approach, this research aims to identify the optimal parameter values that result in superior mechanical properties of the extracted fiber. These optimized parameters can serve as guidelines for the design and operation of automated banana fiber extraction systems. Overall, this research addresses the limitations of manual banana fiber extraction by proposing an automated feeding mechanism and optimizing process parameters. The enhanced efficiency and quality achieved through this approach have the potential to revolutionize the banana fiber industry and promote its utilization in diverse industrial sectors.By elucidating the intricate relationship between process parameters and rheological properties of banana fiber suspensions, this research not only contributes to the fundamental understanding of fiber suspension behavior but also provides valuable insights for industrial applications, particularly in the development of high-performance composite materials.

2. Materials and methods

2.1. Sample preparation

Pseudo-stem of the banana (Musa acuminata Cavendish Subgroup) tree was used for fiber extraction after removing the leaf, upper sheath, and upper part of the plant, corm, and sticky soil particles on it. The rotary action of the blade cuts the banana pseudostem and manually separates the sheaths from the sliced banana pseudostem by hand, beginning with the introduction of banana pseudo-sheaths into the banana fiber extractor machine to extract the fibers. Owing to the quick return mechanism technique in the developed machine, the time required for each pass was 66.67 % lower than that of the manually operated machine. It was also observed that the developed prototype could manage three to four sheaths at a time because the roller and sheet had dimensions of 400 mm and sheaths, sized at 100 mm, were housed within the sheet, allowing for the accommodation of three to four sheaths in one pass, whereas the manual machine could do only one at a time. Subsequently, the obtained fibers were cleaned with water and allowed to dry. The segregated fibers were meticulously dispersed by hand and then carefully separated from the husks and combs. Subsequently, the fibers were dried at room temperature before being meticulously combed multiple times using a cotton carding frame, ensuring their separation; the physical characteristics of the material included a density of 950–750 kg/m3, a length of 1000–2000 mm, a diameter of 0.080–0.250 mm, and a water absorption percentage of 60 %. The banana fiber has an aspect ratio of 1.5 (l/d). At this point, the fiber was ready for measurement of its mechanical properties.

2.2. Mechanical properties of banana fiber

The mechanical characteristics of banana fibers are significant for enhancing strength and longevity. A comprehensive analysis was conducted on various mechanical attributes of banana fibers, including ultimate tensile strength, Young's modulus, and strain percentage.

2.2.1. Ultimatetensile strength

The ability of specimens used in structural applications to resist breaking under tensile stress is one of their most significant and frequently measured features. A banana fiber specimen was examined using a 310 family Universal testing machine (UTM) to determine the force necessary to break it. According to ASTM C1557, the tensile strength was evaluated using standard gauges, and formulae were used to calculate the tensile strength of the fiber [8].

$$\sigma_t = \frac{F_t}{A} \tag{1}$$

Where.

σ_t = tensile strength of fiber, N/mm^2
F_t = Tensile force acting on banana fiber, N; and
A = cross-sectional area of the banana fiber, mm^2.

2.2.2. Young's modulus

Young's modulus is a measure of how a material stretches or compresses when subjected to opposing forces along a specific direction. It quantifies the relationship between the stress and strain experienced during tension. This formula was used to determine the Young's modulus of banana fibers in a study conducted by Du Pont [9].

$$E = \frac{\sigma}{e} \tag{2}$$

Where.

E = Young's modulus of elasticity of banana fiber (N/mm2)
σ = Stress, N/mm^2; and
e = Strain.

2.2.3. Strain percentage

The fiber sample elongated about its initial dimensions before breaking. The strain of the fiber was measured using a universal testing machine according to ASTM D5379 standards. Testing was performed to measure the extent to which the specimen was stretched or elongated to the breaking point. These formulas were used to calculate the elongation percentage of the fiber [10,11].

$$\text{Strain } \% = \frac{L_f - L_i}{L_i} \times 100 \tag{3}$$

Where,
L_f = Fiber length at the point of rupture, mm; and.
L_i = Original length of fiber, mm.

2.3. Experimental design and statistical analysis

Preliminary trials were carried out, and it was observed that the speed of the decorticator, speed of the roller, and clearance between rollers affect the mechanical properties of the banana fiber, which was selected as an independent variable, using a statistical approach, utilizing a second-order polynomial within the framework of the Central Composite Rotatable Design (CCRD) described by Mayers et al. [12]. Sheikh et al. [13] identified three independent variables., Joseph [14], and Sonwane et al. [15], the decorticator speed ranges from (460 rpm, 480 rpm, 510 rpm, 540 rpm, 560 rpm), roller speed ranges from (40 rpm, 50 rpm, 65 rpm, 80 rpm, 90 rpm), and the spacing between rollers ranges from (1 mm, 2 mm, 3 mm, 4 mm, 5 mm) of the banana fiber extractor machine. These variables correspond to the response variables related to the mechanical properties of the fiber, including the ultimate tensile strength, Young's modulus, and strain percentage. Five different levels were chosen for each independent variable to assess their impact on the output parameter. These independent variables were optimized using response surface methodology (RSM) in Design-Expert software version 13.0.5.0. To align with the CCRD design, the five selected levels for each independent variable were transformed into coded variables, which were represented as −1.68 (), −1, 0, +1, and +1.68, as described by Mayers et al., in 2009.Based on the design of expert (DOE) output, a total of 20 experiments with six central points (Table 1) were conducted to calculate the error sum of squares and regression equations, and a 3-D graph was generated to depict the impact of free factors on reactions to the mechanical interaction. A quadratic polynomial condition was fitted, and the model was inspected for the decency of fit utilizing R2 values. The general model is described as follows.

$$Y_i = b_0 + \sum_{i=0}^{3} b_i x_i + \sum_{i=1}^{3} b_{ii} x_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} b_{ij} x_i x_j \quad (4)$$

Where Y is the response and x_i and x_j are the independent variables. where b_0 is the constant, bi is the linear coefficient, bii is the square coefficient, and bij is the interaction coefficient.

The advancement cycles of the autonomous and reliant factors are presented in Table 2. The autonomous variable was taken in range, although the reaction variable, that is, Ultimate tensile strength, Young's modulus was maximized, and strain percentage was minimized. The significance levels (0.1, 1, and 5 %) of the model were determined using an analysis of variance.

3. Results and discussions

3.1. Optimization of independent parameters to obtain maximum strength of the fiber

The study conducted by Hassan et al. [16] employed Response Surface Methodology (RSM) to optimize independent variables using a master software design. Mathematical solutions for optimization, focusing on maximizing attractiveness, were derived. In this context, attractiveness signifies the robustness of an optimal solution, facilitating the attainment of desired outcomes under ideal conditions. Table 1 presents the optimal values for various input and output parameters. The predicted and actual values were compared to validate the response variable under ideal conditions, as illustrated in Fig. 1. The graph indicates a close alignment between the experimental and predicted values for each response variable, demonstrating the areas of strength in the model. Notably, the data points plotted in different colors depict the range of values from minimum to maximum. For ultimate tensile strength and Young's modulus, blue, green, and red colors represent minimum to maximum values, whereas for strain percentage, the colors denote the maximum to minimum data points. This comprehensive analysis provides insights into the reliability and effectiveness of the optimized parameters for enhancing the mechanical properties of banana fibers.

Table 2
Limitations for streamlining independent factors and reaction factors.

Name	Goal	Low	High
Speed of decorticator, rpm	In range	460	560
Speed of roller, rpm	In range	40	90
Clearance between rollers, mm	In range	1	5
Ultimate tensile strength, MPa	Maximize	247.24	679.48
Young's modulus, GPa	Maximize	7.12	26.87
Strain, %	Minimize	2	7

3.2. Effect of independent variables on the mechanical properties of banana fiber

The machine parameters selected were the decorticator speed, roller speed, and clearance between rollers with corresponding response variables (output variable) as the ultimate tensile strength, Young's modulus, and strain percentage of the banana fiber. The effect of machine parameters (independent variables) on the mechanical properties of banana fibers (response variables) was investigated thoroughly and reported under the following sub-headings.

3.2.1. Effect of independent variables on the ultimate tensile strength of banana fiber

Idicula et al. [17], and Patil et al., [18] investigated the ultimate tensile strength of banana fibers and reported values ranging from 458 ± 257 MPa to 543.3–556.7 MPa. Banana fiber, characterized by a lower lignin content compared to fibers such as jute and coir, exhibits varied

Table 1
Combination of CCRD three variable experimental design.

Run	Speed of decorticator, rpm	Speed of roller, rpm	Space between roller, mm	Ultimate tensile strength, MPa	Young's modulus, GPa	Strain, %
1	510	40	3	527.58	18.54	4
2	510	90	3	470.15	13.45	6
3	540	80	2	289.54	9.87	7
4	560	65	3	247.24	7.12	6
5	510	65	3	679.48	25.47	3
6	510	65	1	328.47	10.45	6
7	510	65	5	372.45	11.25	6
8	480	50	4	355.48	10.35	6
9	510	65	3	680.18	26.54	2
10	510	65	3	684.58	26.87	3
11	480	80	2	307.48	8.97	7
12	540	80	4	364.15	11.48	6
13	510	65	3	671.27	24.58	3
14	460	65	3	265.47	8.47	7
15	510	65	3	671.48	25.47	2
16	480	80	4	335.47	12.47	6
17	510	65	3	669.87	24.17	3
18	540	50	4	368.47	12.78	6
19	480	50	2	400.57	14.58	5
20	540	50	2	347.27	13.98	5

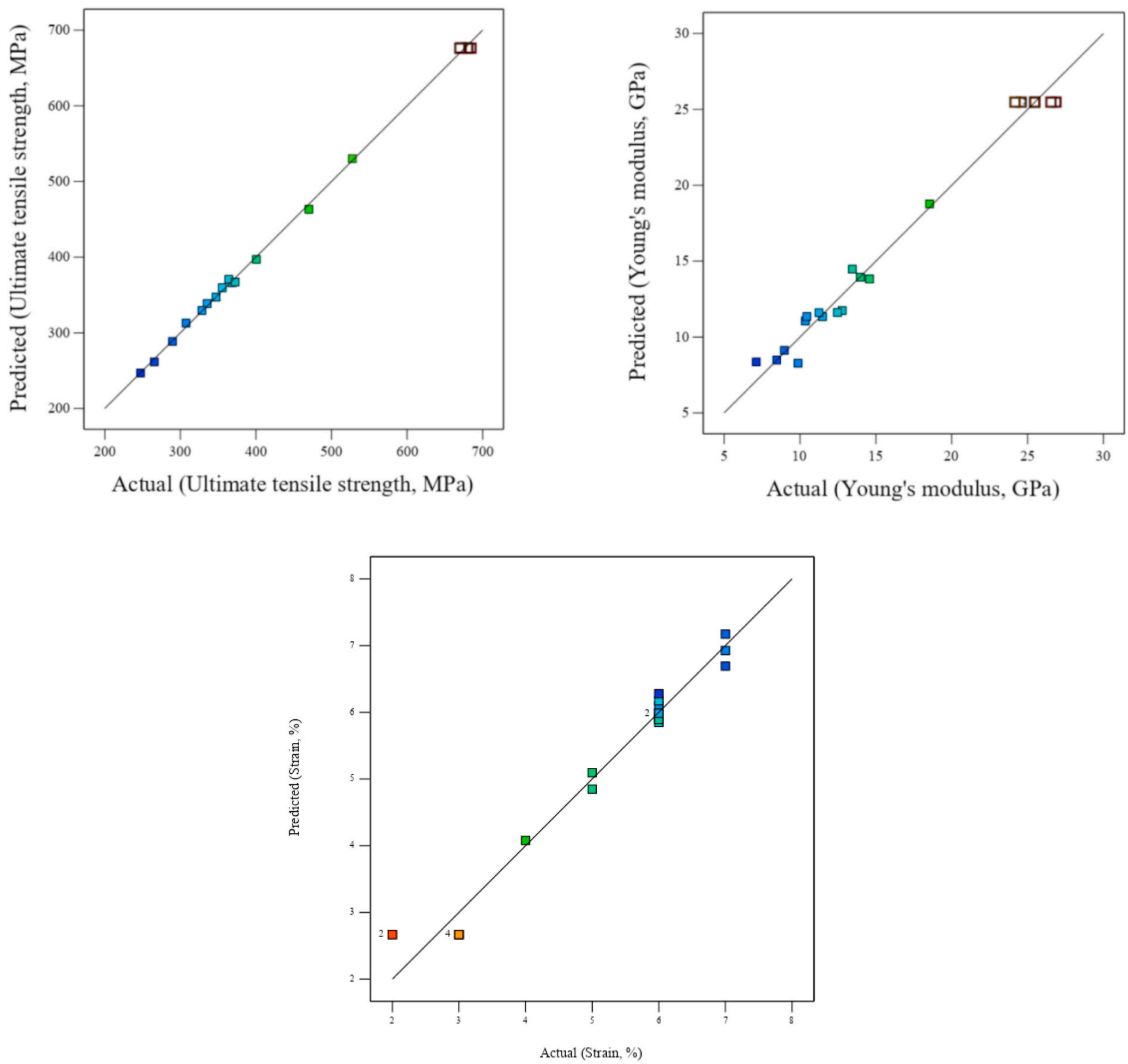

Fig. 1. Degree of precision between actual and predicted values for mechanical properties of the fiber.

mechanical properties in composite materials; in our study, presented in Table 1, the experimental results reveal a broad range of ultimate tensile strength values from 247.24 to 684.58 MPa. Optimal strength was observed at decorticator speeds of 510 rpm, roller speeds of 65 rpm, and a 3 mm spacing between rollers, whereas suboptimal conditions yielded lower tensile strengths (Table 3), indicating a significant influence of operational parameters on ultimate tensile strength ($p < 0.01$), with individual and interactive effects of decorticator speed (DS), roller speed (RS), and roller spacing (RG). The lack of significant lack-of-fit suggests model adequacy.A quadratic regression equation (Equation (5)) was derived, representing the empirical relationship between ultimate tensile strength and operational parameters. The coefficient of determination (R2 = 0.99) confirmed the precision and suitability of this model. This equation offers insights for optimizing banana fiber extraction processes and enhancing the mechanical properties for diverse applications.

$$S_{UT} = 676.27 – 4.41\ D_S - 19.90\ R_S + 11.18\ R_G + 6.38\ D_S R_S + 14.11 D_S R_G + 15.81 R_S R_G - 149.23\ D_S^2 - 63.49\ R_S^2 - 115.96\ R_G^2 \quad (5)$$

where S_{UT}= Ultimate tensile strength, MPa; D_S = decorticator speed, rpm; R_S = roller speed, rpm; R_G = Space between rollers, mm; and R^2 =

Table 3
ANOVA table for the response variable.

Source	df	P Value		
		S_{UT}, MPa	E_Y, GPa	e_s, %
Model	9	<0.0001	<0.0001	<0.0001
D_S	1	0.0277	0.9078	0.2898
R_S	1	<0.0001	0.0029	0.0006
R_G	1	<0.0001	0.8230	1.0000
$D_S R_S$	1	0.0172	0.5866	1.0000
$D_S R_G$	1	<0.0001	0.7456	1.0000
$R_S R_G$	1	<0.0001	0.0116	0.0060
D_S^2	1	<0.0001	<0.0001	<0.0001
R_S^2	1	<0.0001	<0.0001	<0.0001
R_G^2	1	<0.0001	<0.0001	<0.0001
Residual	10			
Lack of fit	5	0.4288	0.3050	0.9264
Pure error	5			
Cor total	19			
R^2		0.996	0.910	0.920
R^2_{adj}		0.998	0.970	0.940

Coefficient of determination.

The analysis reveals that the spacing between the rollers (RG) has a significant impact on the ultimate tensile strength, whereas the interactive effect of the roller speed (RS) and roller spacing (RG) is notably pronounced. Conversely, the decorticator speed (DS) and roller speed (RS) exhibited a negative correlation with the ultimate strength. Fig. 2 illustrates the significant influence of each operational parameter on the ultimate tensile strength. Increasing the decorticator speed from 460 rpm to 560 rpm initially boosts ultimate tensile strength from 531.45 to 679.48 MPa at 480 rpm–510 rpm. Subsequently, a decrease to 522.63 MPa occurs at 510 rpm–540 rpm. This trend is attributed to inadequate beating action at lower decorticator speeds, leading to poor fiber quality, while higher speeds cause fiber damage and reduced diameter, and hence, weaker tensile strength. The peak ultimate tensile strength of 679.48 MPa is achieved at 510 rpm. Similarly, increasing roller speed enhances ultimate tensile strength from 632.67 to 679.48 MPa at 50–65 rpm, followed by a decline to 592.88 MPa at 65–80 rpm. The optimal strength of 679.48 MPa is attained at a roller speed of 65 rpm. Roller clearance also affects ultimate tensile strength, following a similar trend. The strength rises from 549.13 to 679.48 MPa at 2–3 mm, then decreases to 571.48 MPa at 3–4 mm due to increased compression damaging the banana sheath and affecting fiber quality. Thus, maintaining an optimal clearance minimizes sheath damage and moisture retention, ensuring a higher fiber quality and tensile strength.

The comprehensive analysis of varying decorticator speed, roller speed, and the space between rollers reveals their cumulative impact on the ultimate tensile strength (SUT) of banana fibers, as depicted in the three-dimensional representation in Fig. 3. The highest SUT was 684.58 MPa when the decorticator was operated at 510 rpm and the roller speed was set to 65 rpm (see Fig. 4).

The SUT exhibited an initial increase followed by a decrease with an increase in the decorticator speed and space between the rollers. This pattern indicates that the maximum SUT (684.58 MPa) was attained at a decorticator speed of 510 rpm with a 3 mm clearance between the rollers. Similarly, a maximum SUT of 684.58 MPa was achieved at a roller speed of 65 rpm with a 3 mm spacing between the rollers.

Conversely, at higher speeds of the decorticator and roller and increased clearance between the rollers, the minimum SUT was observed. This decline in SUT can be attributed to the reduced fiber interfacial bonding, suggesting that optimal operational parameters are crucial for maximizing the mechanical strength of the banana fiber. This finding underscores the importance of the precise control and optimization of process variables to enhance the quality and performance of banana fibers in various applications.

3.2.2. *Effect of independent variables on Young's modulus of banana fiber*

Various researchers have reported a range of Young's modulus values for banana fiber, with Pappu et al. [1] , who reported a range of 17.14 ± 10.72 GPa. Similarly, Pothan et al. [19] reported 27.69 GPa, Paul et al. [20] reported 29–32 GPa, and Patil et al. [18] reported 9.16 GPa. Our study aligns with these findings, yielding a Young's modulus of 26.47 GPa.Experimental data documented in Table 1 demonstrate a range of Young's modulus values from 7.12 to 26.87 GPa. The highest modulus was observed at a decorticator speed of 510 rpm, roller speed of 65 rpm, and 3 mm gap between rollers, whereas the lowest modulus occurred under different settings.

ANOVA (Table 3) indicated a highly significant model ($p < 0.01$), with the speed of the decorticator (DS), speed of roller (RS), and space between rollers (RG) individually significant, along with their interactions ($p < 0.05$). The lack of a significant lack-of-fit implies model reliability, and the polynomial regression equation depicts the empirical relationship between Young's modulus and operational parameters, with a predicted R^2 value (0.91) in agreement with the adjusted R^2 value (0.97). The high R^2 value (0.98) indicates a close correspondence between the actual and predicted Young's modulus values, confirming the adequacy and suitability of the model. These results underscore the importance of controlling operational parameters to optimize the Young's modulus in banana fibers, facilitating their application in various fields.

The polynomial regression equation

$$E_Y = 25.48–0.04D_S -1.28\ R_S +0.07\ R_G -0.24\ D_SR_S +0.14D_SR_G +1.32\ R_SR_G -6.03\ D_S^2 – 3.13\ R_S^2 -4.95\ R_G^2 \quad (6)$$

where E_Y = Young's modulus, MPa; D_S = decorticator speed, rpm; R_S = roller speed, rpm; R_G = Space between rollers, mm; and R^2 = Coefficient of determination.

The analysis of Young's modulus revealed distinct trends influenced by the decorticator speed (DS), roller speed, and the space between the rollers. As DS increases from 460 rpm to 560 rpm, Young's modulus initially rises from 19.48 to 25.47 GPa between 480 and 510 rpm, then declines to 19.41 GPa within the range of 510 rpm–540 rpm, peaking at 510 rpm. Similarly, increasing the roller speed initially increased the Young's modulus, with a peak value of 25.47 GPa observed at 65 rpm, followed by a decrease. The Young's modulus is also affected by the space between rollers, increasing from 20.45 to 25.47 GPa at 2–3 mm and then decreasing to 20.60 GPa at 3–4 mm.The 3-D representation (Fig. 5) of the interaction effects depicts the fluctuation of Young's modulus with changes in DS, roller speed, and roller spacing. The maximum Young's modulus (26.47 GPa) was achieved at 510 rpm DS and 65 rpm roller speed. This finding aligns with that of Bhatnagar et al.

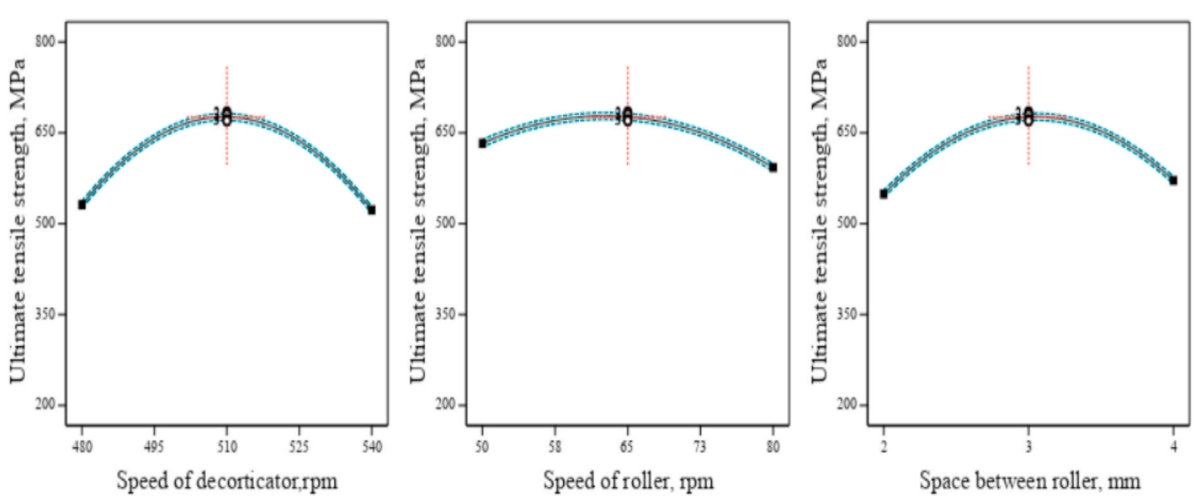

Fig. 2. Effect of speed of decorticator, speed of roller, and space between rollers on the ultimate tensile strength of the fiber.

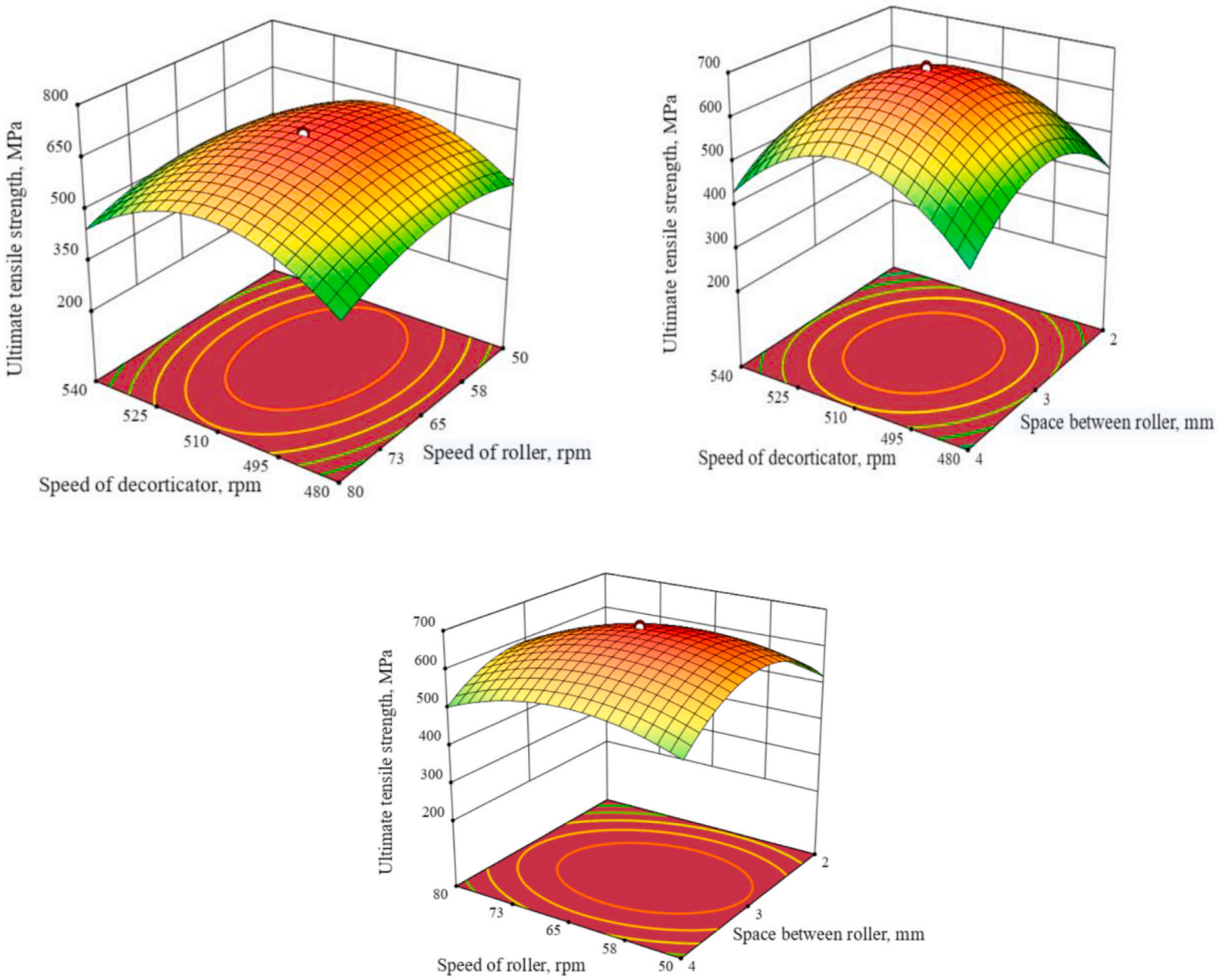

Fig. 3. Interaction effect of the independent variable (speed of decorticator, speed of roller, and clearance between rollers) on the ultimate tensile strength of the banana fiber.

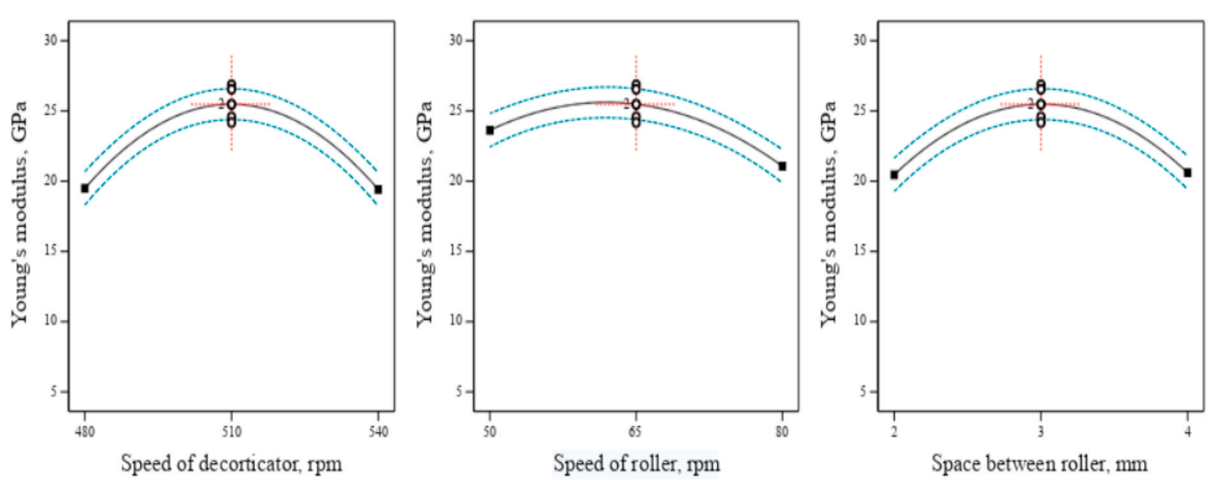

Fig. 4. Effect of speed of decorticator, speed of roller, and space between rollers on theYoung's modulusof the fiber.

[21], who reported a range of 27–32 GPa for banana fiber. Optimal conditions for maximizing Young's modulus include a DS of 510 rpm and a 3 mm gap between rollers. Similarly, the maximum Young's modulus was established at 26.47 GPa with a roller speed of 65 rpm and a 3 mm space between rollers (Fig. 4). These findings underscore the importance of precise control over operational parameters to enhance the mechanical properties of banana fibers.

3.2.3. Effect of independent variables on the strain percentage of banana fiber

A previous study by Joseph et al. (2002), Pothan et al. [19], Idicula et al. [17], Paul et al. [20], and Patil et al. [18] reported strain

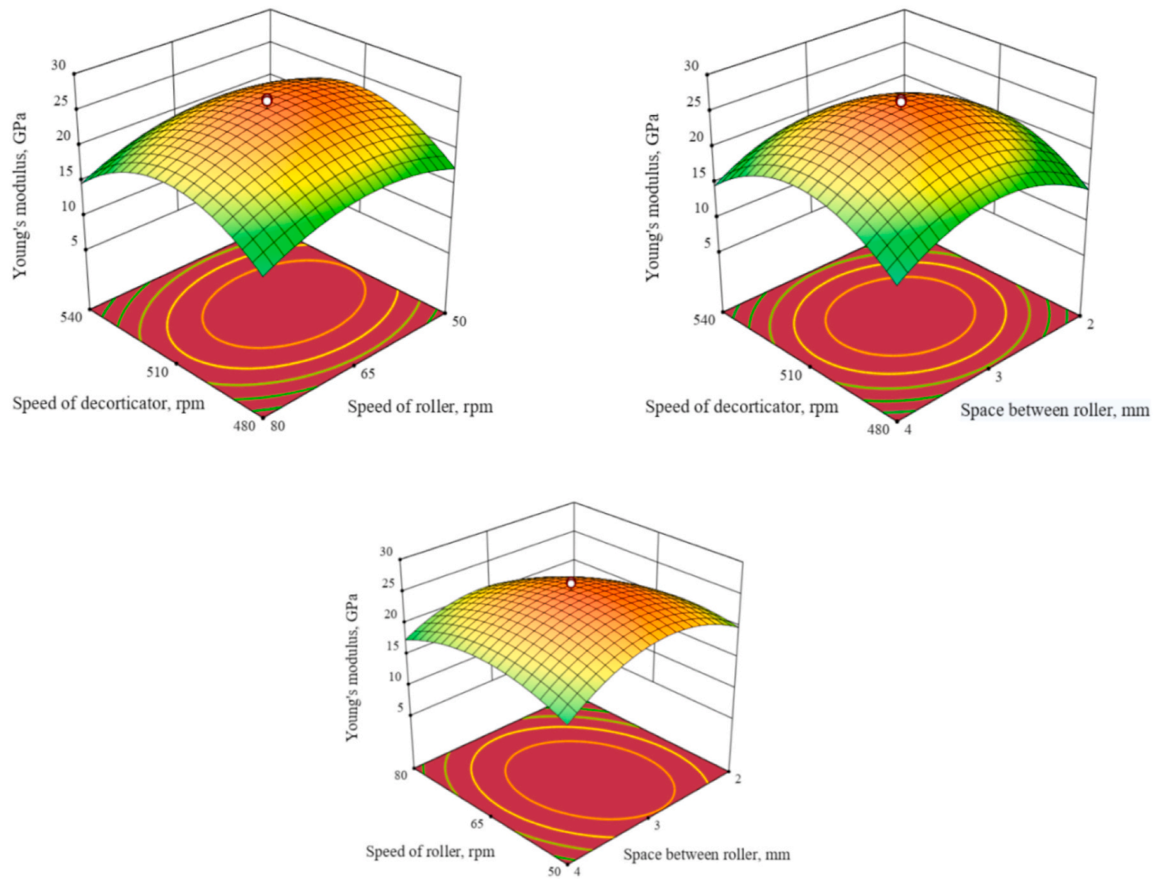

Fig. 5. Interaction effect of the independent variable (speed of decorticator, speed of roller, and clearance between rollers) on the Young's modulus of the banana fiber.

percentages (elongation, %) ranging from 2 % to 7 % for banana fiber, which is consistent with our findings. The experimental data presented in Table 1 demonstrate a range of strain percentages from 2 % to 7 %. The lowest strain percentage was observed at a decorticator speed of 510 rpm, a roller speed of 65 rpm, and a 5 mm clearance between rollers, while the highest strain percentage occurred under different settings. ANOVA analysis (Table 3) indicated the significance of the model at a 1 % level of significance. Individual parameters, such as decorticator speed (DS), roller speed (RS), and gap between rollers (RG), along with their interactions, were found to be significant. The validation of the response variable was confirmed by comparing the actual and predicted values, as depicted in Fig. 1, showing a close alignment between the experimental and predicted strain percentages, indicating no significant lack of fit, and establishing an empirical relationship between strain percentage and the independent parameters, highlighting the importance of decorticator speed, roller speed, and gap between rollers in influencing strain percentage. These findings contribute to a better understanding of the mechanical behavior of banana fibers and aid in optimizing extraction processes for various applications.

The model yielded a predicted R-squared value (R^2) of 0.92, which was supported by the adjusted R-squared value of 0.94. The high R-squared value underscores the degree of agreement between the actual and predicted values of the strain %, confirming the adequacy and suitability of the fitted model. The second-degree polynomial regression equation and its corresponding coefficient of determination (R^2) are presented in equation (4.7).

$$e_S = 2.67–0.12\ D_S + 0.54\ R_S - 0\ R_G - 0\ D_S R_S + 0\ D_S R_G - 0.5\ R_S R_G + 1.34\ D_S^2 + 0.82\ R_S^2 + 1.17\ R_G^2 \quad (7)$$

where e_s = Strain, %, MPa; D_S = Speed of decorticator, rpm; R_S = Speed of roller, rpm; R_G = Space between rollers, mm; R^2 = Coefficient of determination.

The strain percentage (strain %) of banana fibers was influenced by each independent variable, as shown in Fig. 6. The figure illustrates that as the decorticator speed (DS) increased from 460 rpm to 560 rpm, the strain % initially decreased from 4.14 % to 3 % within the range of 460 rpm–510 rpm, and then increased from 3 % to 3.89 % within the range of 510–560 rpm. The highest and lowest strain percentages were 4.14 % and 3 % at decorticator speeds of 480 and 510 rpm, respectively. Similarly, the strain % decreased and then increased within the range of 40–90 rpm as the roller speed increased. The highest strain % was observed at a roller speed of 80 rpm (4.02 %), whereas the lowest was observed at 65 rpm (2.5 %). The strain % decreased as the space between rollers increased, declining from 3.84 % to 2.5 % at 2–3 mm and then increasing from 2.5 % to 3.84 % at 3–4 mm clearance.The 3-D representation in Fig. 7 illustrates the interaction effects between DS and roller speed, DS and space between rollers, and roller speed and space between rollers on strain %. It was observed that the strain % initially decreased and then increased with increasing DS and roller speed. The minimum strain % (3 %) was observed at 510 rpm DS and a roller speed of 65 rpm. Furthermore, the strain % initially decreased and then increased with increasing DS and space between rollers, and similar results were observed for roller speed and space between the rollers. The lower strain % observed in our study compared to others indicates greater fiber strength, suggesting promising applications in natural fiber composites for lightweight and high-strength materials.

3.2.4. Optimization of independent parameters for the different dependentparameters

The opportunity to obtain pertinent results from the system when

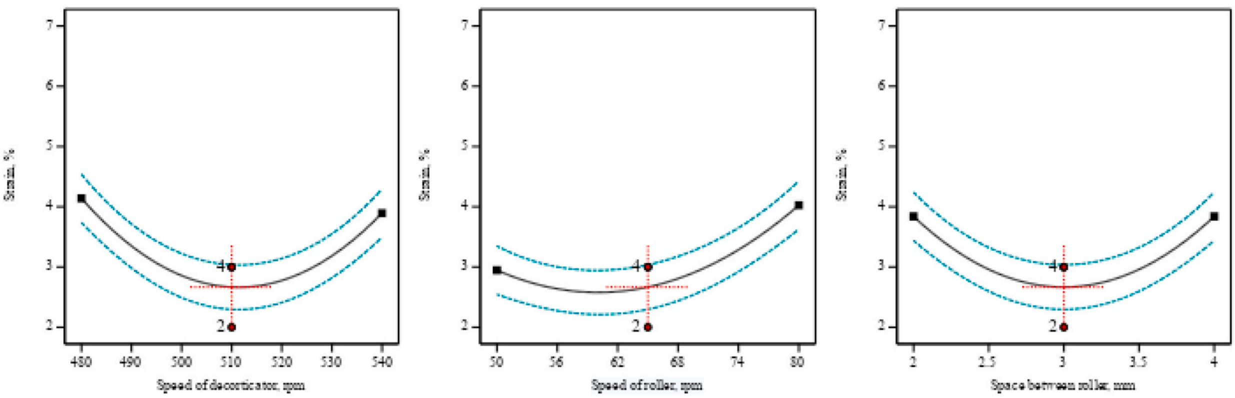

Fig. 6. Effect of each independent parameter on the strain percentage of the banana fiber.

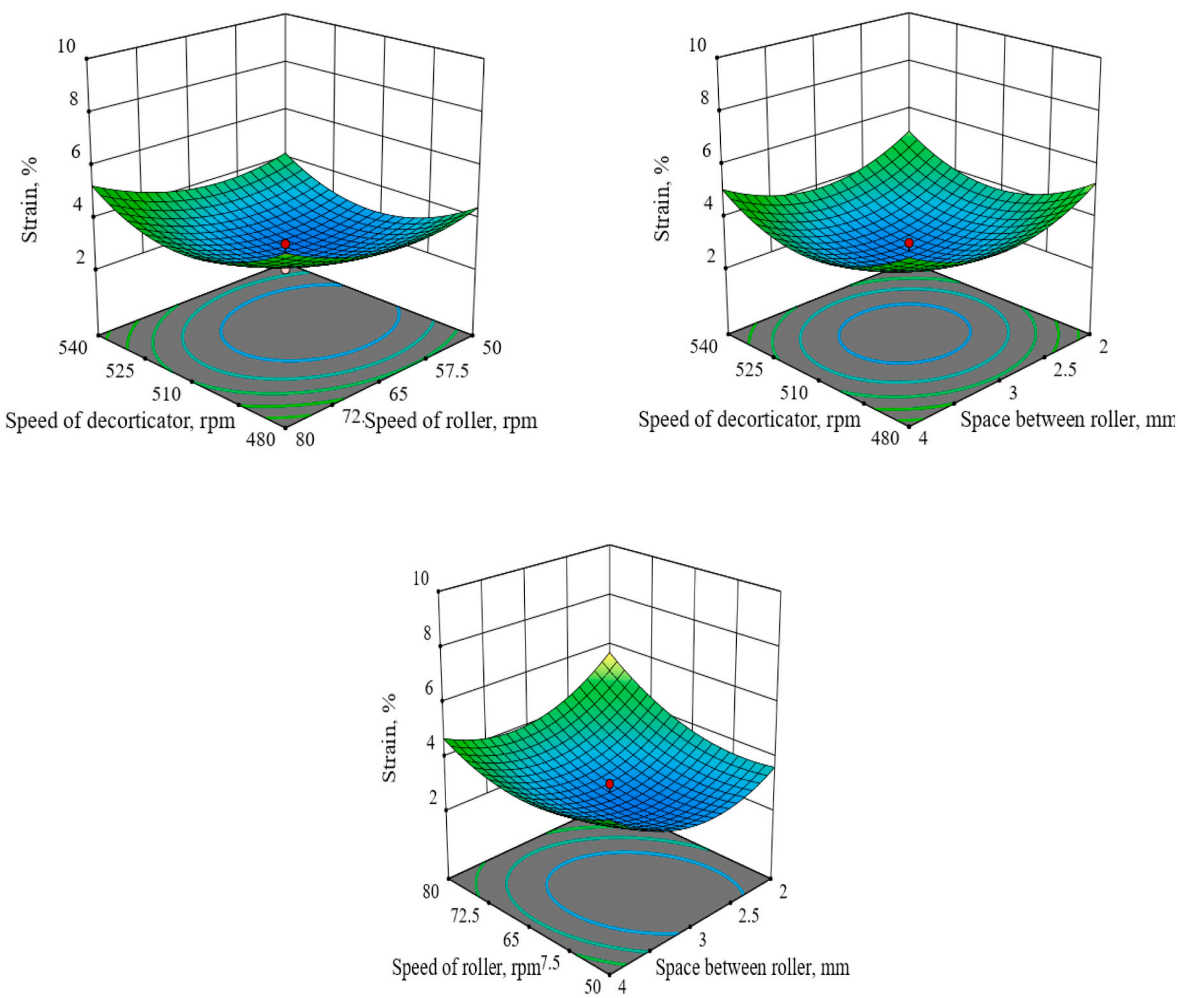

Fig. 7. Interaction effect of the independent variable (speed of decorticator, speed of roller, and clearance between rollers) on the strain percentage of the banana fiber.

employed under optimum conditions was determined by the desirability of an optimum solution that measures the strength of the variables [22]. The highest desirability (0.932) was observed for the optimum solution, and a graphical representation of the numerical solution is shown in Fig. 8.The optimum values of the decorticator speed, roller speed, and clearance between the rollers were found to be 510.28 rpm, 61.74 rpm and 2.98 mmrespectively. The optimum values of the ultimate tensile strength of the fiber, Young's modulus of the banana fiber, and strain percentage of the banana fiber were 676.345 MPa, 25.63 GPa and 2.59 % respectively. The validation of thevalues of optimized independent variables, a performance testing was conductedby fixing the optimum values of the speed of decorticator, speed of roller and spacebetween rollers.

The predicted and actual values after testing at the optimum value of the independent parameter are listed in Table 4. The test results showed that the ultimate tensile strength, Young's modulus, and strain percentage of the banana fiber were 679.48 MPa,25.47 GPa and 3 %, respectively, with predicted values of 676.345 MPa, 25.63 GPa and 2.59

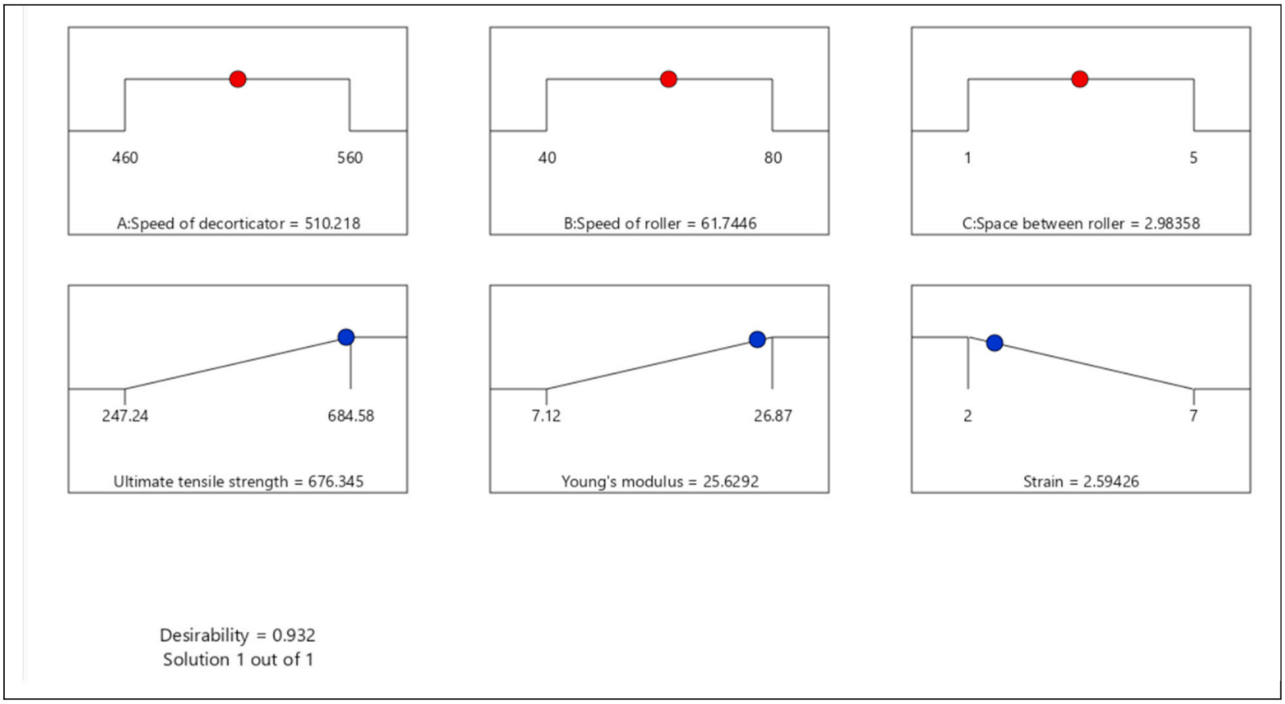

Fig. 8. Optimized value of independent variables with different dependent parameters.

Table 4
Optimum solution of independent parameter on the response variables.

Parameters	Predicated value	Actual value
Ultimate tensile strength, MPa	676.345	679.48
Young's modulus,GPa	25.6292	25.47
Strain, %	2.594	3

Table 5
Combination of CCRD three variables experimental design for time taken each pass, sec.

Run	Speed of decorticator, rpm	Speed of roller, rpm	Space between roller, mm	Time taken for each pass, sec
1	510	40	3	14
2	510	90	3	12.8
3	540	80	2	12.4
4	560	65	3	11.6
5	510	65	3	13.33
6	510	65	1	13.33
7	510	65	5	13.33
8	480	50	4	15.6
9	510	65	3	13.33
10	510	65	3	13.33
11	480	80	2	13.66
12	540	80	4	12.4
13	510	65	3	13.33
14	460	65	3	15.2
15	510	65	3	13.33
16	480	80	4	13.66
17	510	65	3	13.33
18	540	50	4	14.4
19	480	50	2	15.6
20	540	50	2	14.4

%, respectively. The data revealed that the actual and predicted values were closer to each other. This indicates that the values optimized by the software were certified (see Table 5).

The findings of this study underscore the efficacy of both parameter optimization and automation in enhancing the quality, efficiency, and feasibility of banana fiber extraction [23]. By automating the feeding process and employing a systematic optimization approach, this study not only addresses the challenges associated with labor-intensive extraction, but also provides valuable insights into the complex relationship between process parameters and the resulting fiber properties.

Table 6
ANOVA table for the response variable.

Source	df	P Value
		Time taken for each pass, sec
Model	9	0.0280
D_S	1	0.9169
R_S	1	0.3216
R_G	1	0.0106
D_SR_S	1	0.1982
D_SR_G	1	0.0521
R_SR_G	1	0.0257
D_S^2	1	0.1040
R_S^2	1	0.0387
R_G^2	1	0.9596
Residual	10	
Lack of fit	5	0.9324
Pure error	5	
Cor total	19	
R^2		0.923
R^2_{adj}		0.932

3.2.5. *Effect of independent variables on the time taken for each pass of extracting banana fiber*

The presented table (Table 5) outlines the performance of a banana fiber extractor machine across various trials, focusing on parameters such as the time taken for each pass based on decorticator speed, roller speeds, and roller spacing. The time taken for each pass ranged from 11.6 to 15.6 s, reflecting the variability in machine efficiency. Notably, the optimal pass time was identified at 13.33 s, achieved through specific settings: decorticator speed set at 510 rpm, roller speed at 65 rpm, and roller spacing of 3 mm. It is crucial to highlight that this optimal time was not determined solely by minimizing the pass duration but rather by prioritizing the quality of the extracted banana fiber. This underscores the importance of balancing operational speed with product quality in industrial processes. By selecting parameters that yield the best fiber quality, even if it implies a slightly longer processing time, the overall efficiency and effectiveness of the fiber extraction process can be optimized, ensuring a high-quality end product [24] (Table 6).

4. Conclusion

The investigation into the mechanical properties of banana fibers, focusing on variations in decorticator speed, roller speed, and clearance between rollers, has provided valuable insights. The study revealed the significant impact of these process parameters on the quality and strength characteristics of banana fibers, highlighting their interdependence and the need for precise control. The observed range of mechanical properties, including the ultimate tensile strength (247.24–684.58 MPa), Young's modulus (7.12–26.87 GPa), and strain percentage (2–7%), underscores the versatility and potential of banana fiber for diverse applications. Optimization of extraction processes, such as decorticator speed (510 rpm), roller speed (65 rpm), and clearance (3 mm), maximizes fiber strength which can emphasize the importance of optimizing the extraction process for consistent results.Through meticulous experimentation, the optimal combination of variables emerged, maximizing banana fiber strength. This synthesis of automated technology and optimization methodologies presents a promising opportunity to revolutionize banana fiber extraction and foster sustainable and economically viable practices. By advancing our understanding of process-property relationships in natural fiber extraction processes, this research not only contributes to the field, but also opens doors to diverse industrial applications requiring high-quality natural materials. Ultimately, this work paves the way for a more sustainable future, where natural resources are utilized efficiently to meet the demands of various industries while minimizing the environmental impact.

CRediT authorship contribution statement

Shubham Pandey: Writing – original draft. **R.K. Naik:** Supervision. **Vinay Kumar Pandey:** Project administration. **Shivangi Srivastava:** Validation. **Gulden Goksen:** Writing – review & editing, Formal analysis. **Shivam Pandey:** Writing – review & editing. **Sarvesh Rustagi:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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