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Combined Effect of Carding Machine Process Parameters on Yarn Properties; Process Optimization

Kombinirani vpliv procesnih parametrov mikalnika s pokrovčki na lastnosti preje: optimiziranje procesov

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Abstract

Yarn tensile properties, unevenness, and irregularities are the most important properties of the yarn quality parameters that determine the fabric's mechanical properties and appearance. In the current study, the combined effect of carding machine parameters (cylinder speed, flat speed, cylinder to flat setting, and taker-in speed) on yarn properties (yarn strength, elongation, unevenness, and total yarn imperfection) have been examined. In this research, 40 samples of open-end yarn were produced and each of them was tested for their strength, elongation, unevenness, and imperfection. Design-expert 7.0.0 software and Factorial designing have been employed to analyze the results. The results from statistical analysis have showed that increasing the gap between the cylinder and flat setting and increasing the taker-in speed increased yarn unevenness and increasing cylinder speed, flat speed, and taker-in speed increased total yarn imperfection significantly. Similarly, increasing the flat speed, cylinder speed, and taker-in speed as well as increasing the gap between the cylinder and flat reduced yarn strength and elongation significantly.

Keywords: yarn; process parameters, optimization, strength, unevenness, yarn imperfection

Izvleček

Natezne lastnosti, neenakomernost in nepravilnosti preje so najpomembnejši parametri kakovosti preje, ki vplivajo na njene mehanske lastnosti in videz. V raziskavi je bil proučen kombiniran učinek tehnoloških parametrov mikalnika (hitrosti mikalnega bobna, hitrosti mikalnih pokrovčkov, vzajemne nastavitve razdalje med mikalnim bobnom in pokrovčki in hitrosti dovajalnega valja) na lastnosti preje (trdnost, raztezek, neenakomernost in druge nepravilnosti). Za namen raziskave je bilo izdelanih 40 vzorcev rotorske preje. Izmerjeni so bili trdnost, raztezek, neenakomernost in t. i. skupne nepravilnosti preje. Za analizo rezultatov sta bili uporabljeni programski orodji Design-expert 7.0.0 in Factorial designing. Statistična analiza je pokazala, da sta povečanje razdalje med mikalnim bobnom in pokrovčki in povečanje hitrosti dovajalnega valja vplivala na povečanje neenakomernosti preje; povečanje hitrosti mikalnega bobna, hitrosti pokrovčkov in hitrosti dovajalnega valja pa je statistično pomembno vplivalo na skupne nepravilnosti preje. Podobno so povečanje hitrosti pokrovčkov mikalnika, hitrosti mikalnega bobna, hitrosti dovajalnega valja in tudi razdalja med mikalnim bobnom in pokrovčki vplivali na znatno zmanjšanje trdnosti in raztezka preje.

Ključne besede: preja, tehnološki parametri, optimizacija, trdnost, neenakomernost, nepravilnost preje

1 Introduction

The two well-known sayings, ‘the card is the heart of the spinning mill’ and ‘well-carded sliver is half spun’– demonstrate the enormous significance of carding for the end result of the spinning operation. The operation of the card shows the highest correlation to quality and also to productivity [1, 2]. Carding is the most important process in spinning. It contributes a lot to the quality of the yarn. Speeds (flat speed, taker-in speed, and cylinder speed) and settings (licker-in and feed plate, licker-in and under casing elements, cylinder and flat tops, between the cylinder and doffer, and so on) are process parameters which shall be controlled to produce good quality yarn with relatively low production cost.

Cylinder wire selection depends upon cylinder speed, the raw material to be processed, and the production rate. Wire front angle depends mainly on cylinder speed and the coefficient of raw material friction. The cylinder speed in turn depends upon the production rate. Higher production means that more working space for the fibre is required. It is the wire that keeps the fibre under its influence during carding operation [3]. Therefore, the space within the wire should be increased for higher production. Higher cylinder speed also increases the space required for the fibre. Therefore, a higher cylinder speed is required for higher production [4, 5].

The higher the cylinder speed is, the higher the centrifugal force created by the cylinder which tries to eject the fibre from the cylinder, along with the trash. Low front angle with too low cylinder speed and high frictional force will result in a bad quality of card sliver due to a decreased fibre transfer from the cylinder to the doffer [6, 7]. Hence, recycling of fibres will take place, which results in more neps and entanglements. The movement of the fibres towards the tip of the tooth coupled with centrifugal action demands an acute front angle to hold the fibre in place during carding [8].

The basic function of the doffer is to strip the fibres from the Cylinder. Licker-in plays a major role in opening the fibre tufts. A higher number of rows per inch gives better results. If the wire pitch is not sufficient, it can be compensated by increasing the licker-in speed. However, higher licker-in speeds for fine and long cotton will rupture the fibres [8]. The setting between the cylinder and doffer is the closest setting in the card. This setting mainly depends upon the cylinder speed, a hank of the delivered sliver, and the type of wire. If the setting between the cylinder and the doffer is very close, the wires will get polished, which will affect the fibre transfer. If the setting is too wide, the fibres will not be transferred to the doffer from the cylinder, hence the cylinder will get loaded. While processing synthetic fibres, cylinder loading will badly affect the yarn quality. The most critical setting in a carding machine is between the cylinder and flat tops. The closer the setting between the cylinder and flats is, the better the yarn quality is. Neps are directly affected by this setting. A very close setting increases flat waste. For processing cotton, the setting can be 0.25, 0.2, 0.2, 0.2, 0.2 mm [9]. Research results have showed that increasing the speed of the licker-in increased fibre rapture, yarn imperfection, and yarn hairiness and decreased single yarn strength. The increase in fibre rapture is due to a higher opening point-density, which results in a higher intensity of beating. The rise in fibre rapture increases short-fibre content, thus an increase in yarn imperfection and deteriorated single yarn strength [10]. However, the yarn unevenness (U %) and the card cleaning efficiency improve with higher licker-in speeds [11, 12].

Single yarn strength reduces with the increasing production rate of the carding machine. This is attributed to more fibre transfer efficiency leading to less fibre opening and parallelization in the sliver [13]. The neps level in the card sliver reduces when the point density of top flats is increased, minimizing the yarn imperfection. This is attributed to the intensified opening of neps [14].

The yarn unevenness increased with an increase in the card production rate due to poor carding and higher cylinder loading. The total yarn imperfections increase as the production rate increases and cylinder speed is reduced, attributed to more cylinder loading [15].

The purpose of this study is to research the combined effect of cylinder speed, flat speed, taker-in speed, and cylinder to flat setting on yarn properties like yarn strength, yarn imperfection yarn unevenness, and yarn elongation, which has not been studied so far.

2 Materials and methodology

2.1 Materials

Cotton fiber: 100% cotton fiber with the following property was used to manufacture the yarn (Table 1). The spinning consistency index (SCI) is a calculation for predicting the overall quality and spinnability of the cotton fiber.

2.2 Methods

2.2.1 Sliver production

Forty card slivers have been produced on a carding machine (C70), by varying the carding machine setting as stated in Table 2 at Alameda Textile share company, Adwa, Ethiopia. Forty 5,905 tex draw frame slivers (five-card slivers of each were made into one draw frame sliver) were produced on breaker and finisher draw frame machine with the model (RSB D45) and (SB D45), respectively. The machine setting of the draw frame was the same for the production of all slivers.

2.2.2 Yarn production

Forty 24.6 tex rotor spun yarn with twist of 860 m^{-1} were produced on a rotor spinning machine (R40 rotor spinning) at Almeda Textile share company, Almeda, Ethiopia. The feeding speed (0.425 m/min), opening roller speed (7500 min^{-1}), rotor speed (90,000 min^{-1}), and delivery speed (102 m/min) of rotor machine settings were kept constant during the production of all yarns.

2.2.3 Statistical optimization and experimental design of the fabric production process

Design expert 7.0.0 software was used in the optimizations of the yarn production. Design expert software was used as it is well-suited for engineering and science and it focuses on empirical design and optimization of the process parameters. The independent variables used were: cylinder speed, flat speed, cylinder to flat setting and taker-in speed of the carding machine, and the responses were: yarn strength (centinewton/tex), yarn elongation (%), yarn unevenness (Um %), and yarn total imperfections (in number) of the rotor spun yarn. 40 experiments (Table 2) were performed by design expert 7.0.0 software to optimize the machine setting. The statistical significance of the model and variables was determined by ANOVA at 5% significance level [16]. Yarn strength, unevenness, elongation, and imperfection (response factors) were analyzed by ANOVA and 3D response surface plotting.

2.2.4 Characterization of yarn property

To examine the combined effect of the independent variable of the carding machine (cylinder speed, flat speed, cylinder to flat setting, and taker-in speed) on yarn strength, unevenness, elongation, and total yarn imperfection, the following tests were conducted and analyzed:

(a) Effect of cylinder speed, flat speed, cylinder to flat setting, and taker-in speed on yarn unevenness

Unevenness and imperfection of the yarn were determined as per ASTM D1425/D1425M-14(2020). *Standard test method for evenness of textile strands using capacitance testing equipment*. Each sample was tested with five replicas and the average values were taken for analysis [17].

(b) Effect of cylinder speed, flat speed, cylinder to flat setting, and taker-in speed on yarn strength and elongation

Strength and elongation of the yarn were determined as per ASTM D1578-93(2016) *Standard test method for breaking strength of yarn in skein form*. Each sample was tested with five replicas and the average values were taken for analysis [18].

3 Results and discussions

3.1 Optimization of machine setting using factorial design

Yarn strength, elongation, unevenness, and imperfection are essential properties of yarn that must

Table 1: Cotton fiber specification for yarn production

Cotton	Spinning consistency index, SCI	Moisture content (%)	Upper half mean length, UHML (mm)	Uniformity index, UI (%)	Short fibre, SF (%)	Strength (cN/tex)	Elongation (%)
Avg.	82	5.1	25.96	76.7	14.7	23.2	6.2

be controlled to fulfill the standard required by the user [19, 20]. Yarn strength and elongation are important parameters in determining the durability and serviceability of the fabric made from the yarn and unevenness and imperfection are related to the appearance and ends down of yarn during yarn manufacturing [14]. The combined effect of flat speed, cylinder speed, cylinder to flat setting, and taker-in speed of the carding machine on the strength, elongation, unevenness, and imperfection of yarn has been studied and optimized using design expert 7.0.0 software and factorial design. The design allows random manufacturing of different samples, giving a chance to produce the same samples at different times, to avoid other nuisance factors. Generally, the process factors are designed to be at the carding section and are analyzed for their effects on rotor spun yarns.

3.2 Fitting the models

The dependent variables (strength, elongation, evenness, and imperfection) and independent variables (cylinder speed, flat speed, cylinder to flat setting, and taker-in speed) were examined to draw regression equations showing an empirical relationship between the tested variable and the machine settings in the actual units, which can predict the responses under the given range. Therefore, to determine the factor levels which yield optimum strength, elongation, evenness, and total yarn imperfection of the yarn, mathematical regression between dependent and independent variables (equations 1–4) were developed.

The final equations in terms of the actual factors generated by the factorial design were:

$$Yarn\ uneveness = +22.80 - 0.066 * A - 0.43 * B + 60.3 * C - 0.0186 * D - 0.025 * A * C + 8.3 * A * D - 0.056 * C * D \tag{1}$$

$$Yarn\ strength = +119.05 - 0.366 * A + 8.05 * B + 16.76 * C - 0.082 * D + 0.27\ A * C + 2.91424E - 004 * A * D - 00.126 * C * D \tag{2}$$

$$Yarn\ Elongation = +18.43 - 0.1327 * A + 39.09 * B + 101.06 * C - 0.0212 * D + 4.30303E - 004 * A * C + 1.38212E - 004 * A * D - 0.11 * C * D \tag{3}$$

$$Total\ yarn\ imperfection = +1535.466 + 2.47 * A + 450.83 * B + 3047.24 * C + 1.02 * D - 3.99 * A * C - 1.42121E - 003 * A * D - 1.41 * C * D \tag{4}$$

where A is cylinder speed, B is flat speed, C is cylinder to flat setting and D is taker-in speed.

3.3 Examination of model adequacy

Model individual significance and regression goodness was evaluated by ANOVA. In this research, ANOVA was used to analyze the selected model and model coefficient using 95% significant level. The regression terms and the model are said to be significant when the p-value is less than 5%. As shown in Tables 3 and 4, the model is significant statistically ($p < 0.05$) for the cylinder to flat setting and taker-in speed for unevenness, cylinder speed, flat speed and taker-in speed for total yarn imperfection and all independent variables (flat speed, cylinder speed, cylinder to flat setting and taker-in speed) were significant for the responses (yarn elongation and yarn strength).

3.4 Effect of flat speed, cylinder speed, cylinder to flat setting, and taker-in speed on yarn unevenness and total yarn imperfection

Unevenness and total imperfection of yarn are very important parameters of yarn which deals with variation in yarn count or fineness along the yarn length, negatively influencing the yarn as well as the fabric properties [21]. In the current study, the combined effects of cylinder speed, flat speed, cylinder to flat setting, and taker-in speed on yarn unevenness and yarn total imperfection have been

Table 2: Designed experiment and test results for rotor spun yarns

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3	Response 4
Run	A: Cylinder speed (min^{-1})	B: Flat speed (m/min)	C:Cylinder to flat setting (mm)	D: Taker-in speed (min^{-1})	Yarn evenness, Um (%)	Yarn strength (cN/tex)	Elongation (%)	Total yarn imperfection, TYI
1	410	0.2	0.35	960	9.69	8.89	4.67	16
2	465	0.22	0.35	960	10.05	9.38	5.5	6
3	465	0.2	0.35	860	10.05	8.34	4.29	10
4	465	0.22	0.3	860	9.87	6.75	4.68	20
5	465	0.2	0.35	860	10.05	8.34	4.29	10
6	410	0.2	0.3	860	10.03	8.43	4.59	8
7	410	0.2	0.3	860	10.03	8.43	4.59	8
8	465	0.2	0.3	960	10.17	8.1	4.88	5
9	465	0.2	0.3	960	10.17	8.1	4.88	5
10	465	0.22	0.3	860	9.87	6.75	4.68	20
11	465	0.22	0.35	960	10.07	9.38	5.5	6
12	465	0.2	0.35	860	10.05	8.34	4.29	10
13	465	0.22	0.3	860	9.87	6.75	4.68	20
14	410	0.2	0.35	960	9.69	8.89	4.67	16
15	410	0.2	0.3	860	10.03	8.43	4.59	8
16	410	0.2	0.3	960	9.88	8.4	4.76	10
17	465	0.2	0.3	960	10.17	8.1	4.88	5
18	465	0.22	0.35	960	10.04	9.38	5.5	6
19	410	0.2	0.35	860	10.27	9.43	4.97	18
20	410	0.2	0.3	960	9.88	8.4	4.76	10
21	410	0.2	0.3	860	10.03	8.43	4.59	8
22	410	0.2	0.35	960	9.69	8.89	4.67	16
23	465	0.2	0.35	860	10.05	8.34	4.29	10
24	410	0.2	0.35	860	10.27	9.43	4.97	18
25	465	0.2	0.35	860	10.05	8.34	4.29	10
26	465	0.22	0.35	960	10.05	9.38	5.5	6
27	410	0.2	0.3	960	9.88	8.4	4.76	10
28	410	0.2	0.35	960	10.03	8.43	4.59	8
29	465	0.2	0.3	960	10.17	8.1	4.88	5
30	465	0.2	0.3	960	10.17	8.1	4.88	5
31	410	0.2	0.35	860	10.27	9.43	4.97	18
32	465	0.22	0.35	960	10.05	9.38	5.5	6
33	465	0.22	0.3	860	9.87	6.75	4.68	20
34	410	0.2	0.35	860	10.27	9.43	4.97	18
35	410	0.2	0.35	960	10.03	8.43	4.59	8
36	410	0.2	0.3	960	9.8	8.03	5.07	9
37	410	0.2	0.35	860	10.27	9.43	4.97	18
38	410	0.2	0.3	960	9.88	8.4	4.76	10
39	465	0.22	0.3	860	9.87	6.75	4.68	20
40	410	0.2	0.3	960	9.88	8.4	4.76	10

investigated. The ANOVA result in Table 3 revealed that increasing the gap between the cylinder and flat setting and increasing the taker-in speed increased yarn unevenness, and increasing the cylinder speed, flat speed, and taker-in speed decreased total yarn imperfection significantly. Figure 1 (a and b) also shows that the yarn irregularity decreases by decreasing the cylinder to flat setting and decreasing cylinder and taker-in speeds. This is due to the narrow cylinder-flats setting which augments the carding action and enhances the removal of short fibers. Increased speed of the taker-in rises fiber rapture and short fiber content. The increased speed of the main cylinder deters the action of the flats since their speed is comparatively insignificant and an increased centrifugal force on the fibers may disrupt their alignment.

As shown in Figure 1 (c and d), the total yarn imperfection also increases with decreasing cylinder and taker-in speeds, increasing flat speed, and wider cylinder-flat setting. When the speed of the cylinder is reduced, the fiber web is transferred to the doffer instead of spending additional time on the surface of the cylinder, which reduces the chance of additional carding time. This would increase the number of entangled fibers and neps not opened properly. Increased top flats and taker-in speeds, and a narrow cylinder-flat setting intensify the opening of tufts, fiber individualization, and longitudinal orientation and neps removal.

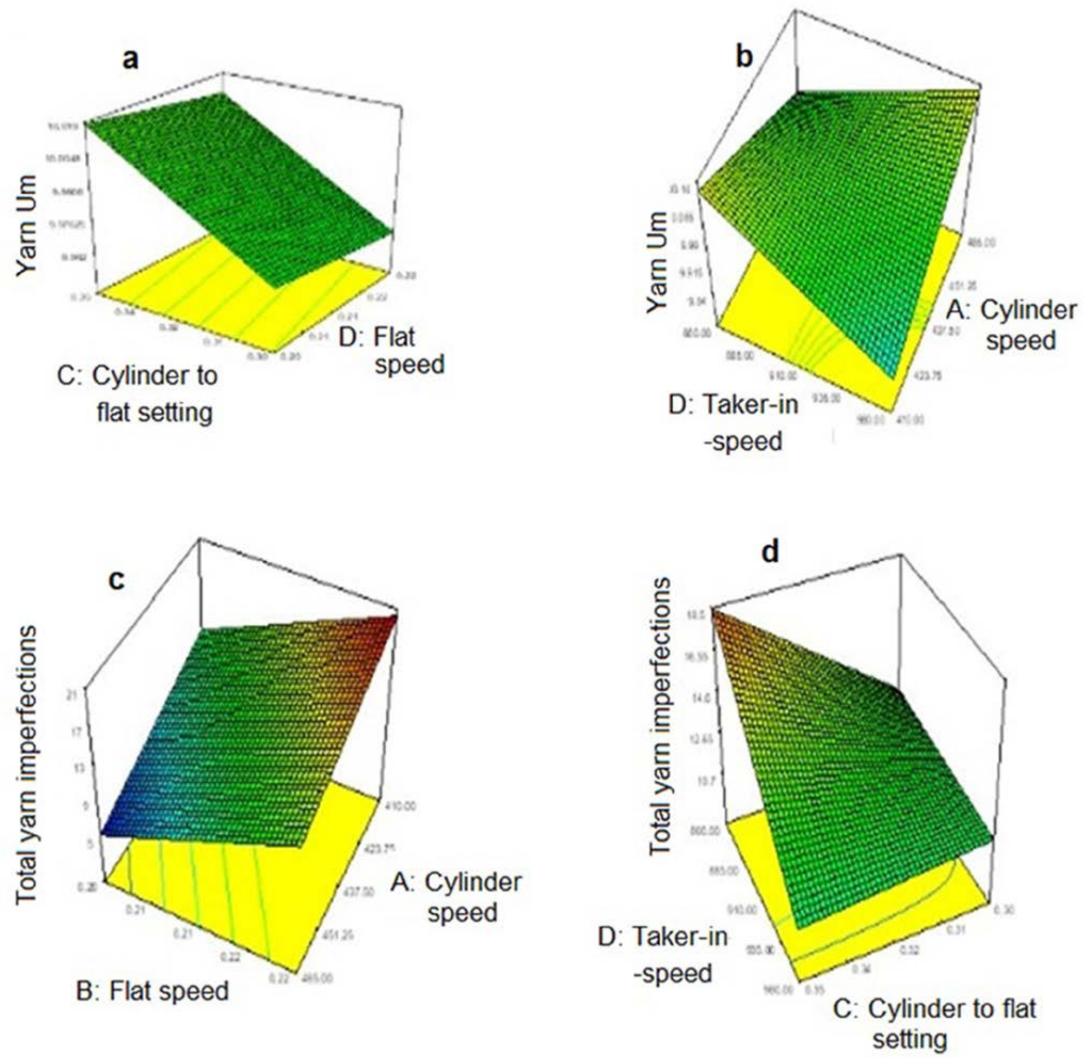

Figure 1: 3D response surface plots indicating effects: a) Cylinder to flat setting and flat speed on yarn Um, b) Taker-in speed and cylinder speed on yarn Um, c) Flat speed and cylinder speed on yarn total imperfection and d) Taker-in speed and cylinder to flat setting on yarn imperfection

Table 3: ANOVA Table for rotor spun yarn unevenness and total yarn imperfection

	Source	Sum of square	Df	Mean square	F-value	p-value
Yarn unevenness	Cylinder speed	1.598E-003	1	1.598E-003	0.2	< 0.6596
	Flat speed	2.153E-003	1	2.153E-003	0.27	< 0.6094
	Cylinder to flat setting	0.065	1	0.065	8.08	< 0.0077
	Taker-in speed	0.092	1	0.092	11.34	< 0.0020
Total yarn imperfection	Cylinder speed	214.8	1	214.8	85.55	< 0.0001
	Flat speed	201.16	1	201.16	82.92	< 0.0001
	Cylinder to flat setting	9.72	1	9.72	4.01	< 0.0537
	Taker-in speed	309.14	1	309.14	127.55	< 0.0001

3.5 Effect of flat speed, cylinder speed, cylinder to flat setting, and taker-in speed on yarn strength and elongation

Yarn strength and elongation are directly related to fabric durability and serviceability. Stronger yarn will result in better fabric durability and serviceability [22]. According to Table 4, the Factorial model used implies that the model is significant. Moreover, the effect of all main factors (cylinder speed, flat speed, cylinder to flat setting and taker-in speed) and the interaction between the cylinder and flat speeds, between cylinder and taker in speeds, the taker-in speed and flat top setting, were statistically significant on yarn strength and elongation. This implies that the above-stated main factors and their interaction affect yarn strength and elongation significantly. An increase of all independent variables reduced the yarn strength and elongation significantly. The yarn strength deteriorated with an increase in carding machine cylinder and taker-in speeds, and narrow cylinder-flat settings attributed to fiber rapture and deteriorated fiber strength. The yarn elongation increases with an increasing flat speed, cylinder speed, taker-in speed, and cylinder to flat setting. Lowered cylinder speeds attributed to intensified opening and greater short fiber removal. The longer and straighter the fibers, the higher is the twist consumption along the yarn axis. When all the produced twists are consumed along the fiber length, the elongation and strength is the greatest.

3.6 Comparison between the optimum and existing configurations

The optimum selected and existing configurations of the components are shown in Table 5. The optimum solution is selected considering yarn strength and elongation as the highest importance since the other properties are not out of range. The yarn strength and elongation are significantly improved without affecting the other properties. However, the software has generated thirty different configurations and corresponding results, allowing the

Table 4: ANOVA table for rotor spun yarn strength and yarn elongation

	Source	Sum of square	Df	Mean square	F-value	p-value
Yarn strength	Cylinder speed	2.3	1	2.3	200.13	< 0.0001
	Flat speed	0.064	1	0.0641	5.59	< 0.0243
	Cylinder to flat setting	11.11	1	11.11	965.9	< 0.0001
	Taker-in speed	1.53	1	1.53	133.31	< 0.0001
Yarn elongation	Cylinder speed	0.49	1	0.49	177.93	< 0.0001
	Flat speed	1.51	1	1.51	551.45	< 0.0001
	Cylinder to flat setting	0.12	1	0.12	42.94	< 0.0001
	Taker–in speed	1.04	1	1.04	380.96	< 0.0001

engineers to select the configurations and solutions according to their priorities.

3.7 Optimization of carding configurations

The optimum setup of the carding machine process parameters is shown in Table 5. The results show the rank of the setups based on their effect on rotor spun yarn (yarn Um%, yarn total imperfections, and Yarn strength & yarn elongation). Thus, the optimum setup of the carding machine parameters would be: cylinder speed (410 min^{-1}), top flat speed (0.20 m/min), cylinder to flat setting (0.35/0.30/0.275/0.25), and taker-in speed (861 min^{-1}). These setups of machine components produce a yarn having Yarn Um% (10.26%), yarn total imperfections (14) yarn strength (9.44 cN/tex), and yarn elongation (5.06%).

4 Conclusion

The cotton yarn has been used for fabric production for several years. The quality of the yarn is key parameter in the production of the yarn to manufacture durable and pleasant fabric. Yarn tensile properties, evenness, and yarn regularity are among the most important properties of the yarn that must be controlled during spinning.

This research aimed at obtaining the optimum carding machine setting to acquire the optimum result of yarn properties (yarn evenness, imperfection, strength, and elongation). The research results have shown that the narrow cylinder-flats setting augments the carding action and enhances the removal of short fibers and the total yarn imperfection increases with decreasing cylinder and taker-in speeds and flat speed. The yarn strength deteriorated with increasing cylinder speed, flat speed, and taker-in speeds, and narrow cylinder-flat settings attributed to fiber rapture and weakened fiber strength.

The yarn elongation increases with increasing flat speed and taker-in speeds and lowered cylinder speeds, attributed to intensified opening and greater short fiber removal. When all the produced twists are consumed along the fiber length, elongation and strength are maximized.

The optimum setup of the carding machine parameters to obtain the maximum possible yarn quality would be; cylinder speed (410 min^{-1}), top flat speed (0.20 m/min), cylinder to flat setting (0.35/0.30/0.275/0.25), and taker-in speed (861 min^{-1}). Future study will seek the effect of the carding machine setting on yarn productivity.

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Table 5: Comparison between the optimum and existing configurations

S/no	Configurations	Existing configuration	Optimum configuration
1	Cylinder speed (min^{-1})	415	410
2	Taker-in speed (min^{-1})	960	861
3	Flat speed (m/min)	0.20	0.20
4	Cylinder-flat gaps from entry to exit positions (mm)	0.30/0.275/0.25/0.2	0.35/0.30/0.25/0.2
Results	Yarn Um (%)	11	10.3
	Yarn total imperfections (ITI)	17	14
	Yarn strength (cN/tex)	7.75	9.4
	Yarn elongation (%)	4.79	5.1

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