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Prioritising Yarn Quality Via Varying Top Roller Hardness: A Fuzzy Application

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Article

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ABSTRACT

In recent years, the spinning or yarn manufacturing sector has seen remarkable technological advancements, emphasizing high-quality yarn production, especially for cotton combed ring spun yarns. In the case of better quality ring spun combed yarn, each part of the ring frame is significant. To fulfil this issue, this study focuses on understanding the impact of the drafting roller hardness on cotton-combed ring-spun yarn quality. It delves into how ten top and bottom roller hardness combinations influence yarn quality parameters. The cotton combed yarns underwent rigorous testing after spinning on ring frames with varying drafting roller hardness. Key quality parameters studied included yarn Imperfection Index (IPI), Unevenness (Ue%), Hairiness (Hi), Elongation at break (Eb%), and Count Strength Product (CSP), and Tenacity (Te). The primary insight was that extreme roller hardness adversely affects all parameters except Elongation at the break value obtained for the shore hardness value of 80/83. Yarns produced using medium-hardness rollers showcased fewer imperfections due to more consistent fibre flow and minimized drafting slippages, resulting in an even twist. These findings are pivotal for the yarn manufacturing industry, hinting at potential refinements in production methods. The usage of the Fuzzy DEMATEL (Decision-Making Trial and Evaluation Laboratory) methodology also determined that Te CSP) and IPI values significantly influence the combed yarn quality when adjusting roller hardness, whereas Hi is the least influential. Therefore, this study offers twofold insights: determining the optimal roller hardness and identifying the most affected quality parameters.

KEYWORDS

yarn quality, cotton combed yarn, ring spinning, drafting roller hardness, fuzzy DEMATEL methodology

INTRODUCTION

Making yarn is essential to spinning and has come a long way from using hand spindles. A vital development component is ring spinning, used to make high-quality yarns for various usages of textiles [1]. The ring frame’s drafting roller is not only significant for the final yarn’s quality variable but also for the overall productivity and efficiency of the whole process [2].

The drafting procedure in ring spinning must be studied in detail to understand the significance of the roller's hardness [3]. The process of drafting prepares the roving for spinning by thinning it out. Three rollers with progressively higher rotational speeds are used in this process to guarantee uniform fibre drawing. Because of the importance of precision and speed, their physical characteristics, especially their hardness, directly impact yarn quality [4]. Inconsistent yarn tension and quality may result if the rollers need a more firm hold on the fibres. However, using too harsh rollers might compromise the yarn's strength and flexibility [5]. The proper roller hardness becomes crucial, balancing price, quality, and productivity [6].

A significant achievement forward in the study of complicated, interrelated criteria that are frequently encountered in yarn quality evaluations has been the development of the Fuzzy DEMATEL (Decision-Making Trial and Evaluation Laboratory) approach [7]. This methodology deploys a combination of fuzzy logic and inferential reasoning. Insights into the intricate connections and significance of different quality attributes can be obtained through this method's meticulous and accurate evaluation of them [8,9].

There is still a lot we are unaware of about ring spinning, namely how the drafting rollers' hardness affects yarn quality. Very few investigations have looked into the exact impacts of roller hardness on particular yarn quality criteria, including the imperfection index, unevenness, hairiness, and tensile strength, according to historical literature. Many studies have focused on the mechanics and results of ring spinning. While prior research has investigated how different roller settings affect fibre strand condensation and migration characteristics, the extensive effect of roller hardness has so far remained unresolved.

This study aims to fill these gaps by analysing the effects of different roller hardness settings on combed yarn quality using the Fuzzy DEMATEL approach. To get the most effective results from top roller hardness optimisation, we focus on a few fundamental research questions:

- How do the top roller hardness and its changes affect the combed yarn quality?
- Which hardness level is suitable for better yarn quality?
- When making yarn, how can we best apply the Fuzzy DEMATEL methodology to prioritize and understand the most influential quality parameters?

The below goals are designed to meet the above research questions:

- To manufacture the combed yarn of 40 Ne with an adjustable roller hardness.
- To comprehensively assess the quality metrics of the yarn produced under these conditions.
- To prioritize the most relevant quality indicators in determining yarn quality by Fuzzy DEMATEL.

Several significant new developments are brought forth by this study that add to the existing database of literature:

- Identifying the hardness range that results in the slightest variation in quality measures can help yarn production become more standardized.

- An innovative technique for evaluating and determining the criticality of numerous quality indicators, Fuzzy DEMATEL, is being applied here for the first time.

The current study contributes to the present existing body of literature by pinpointing the range of hardness that produces the most consistent quality parameters, which can be used to standardise yarn manufacturing. Additionally, it utilises the Fuzzy DEMATEL method to present an entirely novel method for evaluating and ranking the importance of various quality indicators. Besides improving our knowledge of how the drafting roller affects yarn quality, this study offers useful perspectives that could improve textile manufacturing operations by providing proper indications for significant quality indicators.

LITERATURE REVIEW

A Review of the Ring Frame and Its Drafting Zone

The ring-spinning frame, which originated in the nineteenth century, revolutionized the textile industry by providing a reliable mechanism for mass-producing finer, stronger, and more uniform yarns than had previously been possible [10-12].

Several zones in a ring-spinning frame can't be avoided, and the drafting zone is one of them. The drafting zone, located within the ring-spinning frame's complex mechanisms, is crucial to the yarn-making process [13-14].

The ring-spinning frame's drafting zone is crucial to turning roving into yarn. The hardness of the drafting rollers (Figure 1) is significant among the many parameters and components that affect this procedure [15-17]. The appropriate hardness of the rollers provides a consistent and even grip on the fibres, leading to a uniform thickness and structure of the yarn [18-19].

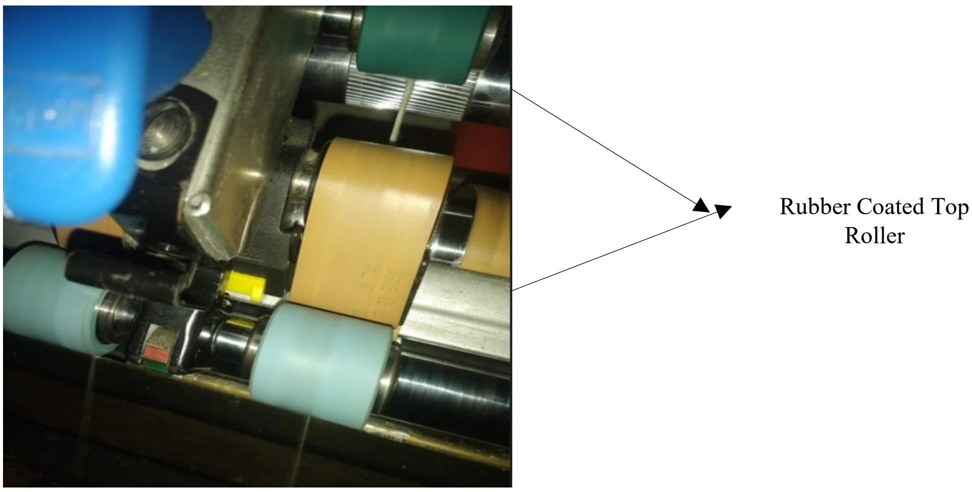

Figure 1. Rubber-coated roller and its settings in the drafting zone

A Detailed Insight on the Fuzzy DEMATEL Methodology

A powerful analytical framework known as Fuzzy DEMATEL (Decision Making Trial and Evaluation Laboratory) handles challenging decision-making issues, particularly those with multifaceted and interconnected factor interactions. The method employs fuzzy thinking to improve DEMATEL's capacity to manage human assessment of uncertainties and ambiguities. Respondents express their thoughts regarding how they feel about the impact of one factor on others using linguistic factors, which are then transformed into numbers that are fuzzy in Fuzzy DEMATEL. Fuzzy values from "zero impact" to "very strong impact" provide a range of impact levels. Comparisons among pairs indicate the degree of immediate association between elements in this input [20-24].

Fuzzy linguistic phrases are transformed into crisp values via computational methods. Fuzzy matrices and normalisation are used to reduce outliers and stabilize data. An influence matrix reveals the system's driving forces and dependent variables by demonstrating how each factor affects others. Visualizing intricate interactions in an interconnected diagram (digraph) is another significant benefit of Fuzzy DEMATEL. The decision-makers can pinpoint actions and plan systematically with this depiction of the system's architecture and dynamics.

Systematic evaluation with Fuzzy DEMATEL benefits the areas of strategic leadership, decision-making, environmental strategy formation, and quality and technology assessment, where elements are interrelated and evaluation parameters are subjective [25-28].

Quality assurance and control are essential across the yarn manufacturing is a very challenging business because complex interactions between variables such as raw material quality, machine settings, environmental conditions, and human intervention are required[29]. Considering the above matters, researchers have developed a systematic method that combines deterministic analysis with fuzzy logic. In essence, DEMATEL is an effective decision-support tool, especially when it is crucial to grasp complex interrelationships and fundamental difficulties [30-33].

Potential Research Gaps

This is even though numerous aspects of ring spinning have been significantly investigated. There is still a lot to learn about how the hardness of the drafting roller significantly impacts yarn quality despite the significant study that has been done on many other elements of ring spinning. Research showed the mechanism of fibre strand condensing on the drafting zone of the ring frame with compact attachment for the compact yarn by changing the applied pressure and the speed of condensing through different lateral positions of the groove [34]. Another study showed the effect of modified soft drafting on the impact of 18.2 Tex cotton combed yarn to reduce the imperfections on that yarn [5]. Moreover, the study was conducted on the fibre migration properties of cotton and nano fibre-based compact yarn through the usual ring frame drafting system [35]. Furthermore, using the Fuzzy DEMATEL provides another novelty of this work. Although much work has been conducted using this methodology to assist real-life practitioners in making proper decisions to improve the conditions of a specific sector. For example, some others researched adequate selection criteria for suppliers to reduce risk and pollution while enhancing organizational productivity using Fuzzy DEMATEL [36]. Another goal is to give a management guide for the chemical industry. Some other study conducted on human and maintenance-related matters for increasing the overall quality of small and medium-sized industries by using combined Fuzzy AHP-TOPSIS and DEMATEL methodology [37]. Moreover, a study on Fuzzy multi-criteria methods (MCDM), including Fuzzy DEMATEL methodology, for prioritizing and selecting composite materials for dental vital in the biomedical industry [38].

Quality Parameters

Unevenness (Ue%)

It provides a percentage value representing the variation in mass along a specified length of yarn. When measuring yarn quality, a lower Um% indicates better consistency [39].

Imperfection Index (IPI)

IPI is the measurement of the thick, and thin places and neps of a certain length of yarn. A greater IPI number implies more abnormalities, which may result in a worse quality yarn [39].

Hairiness (Hi)

Hairiness (Hi) is a measurement of the total length of protruding fibres in one cm cut length of yarn [18].

Count Strength Product (CSP)

CSP strands for Count Strength Product are a crucial quality measurement for yarns, obtained by the multiplication of yarn count (in Ne) and tensile strength (in lbs) respectively [2-4]. In a simple word, it is a measurement of the strength of lea (120 yds) of yarn. For this reason, it helps factories to produce fine and strong yarns, as their customers require [39].

To calculate the CSP, a tensile testing machine is used to pull a piece of yarn until it breaks, noting the greatest force in ibs that the yarn experienced before breaking. Then, by the yarn count tester or a simple wrap reel and a digital weight scale, the yarn count in Ne is obtained. Finally, the CSP value is obtained by multiplying this force value in lbs by the yarn count value in Ne [5].

Tenacity (Te)

Tenacity is a crucial quality metric for measuring the tensile strength of a single yarn before it breaks. It is typically written as a ratio, such as gm/tex or cN/tex. It guarantees every single yarn's accuracy and consistency concerning tensile strength among the yarn lots [39].

Elongation at Break (Eb%)

The percentage of length increment that occurs to the yarn right before it breaks under tension is known as its Elongation at the break [19].

RESEARCH METHODOLOGY

The following section will navigate through every detail that has to be said about the specific stages of the procedure and the overall plan of action. It will cover both the methodology and the steps that are involved.

Research Framework

The whole study's format has conformed to the pattern below in Figure 2.

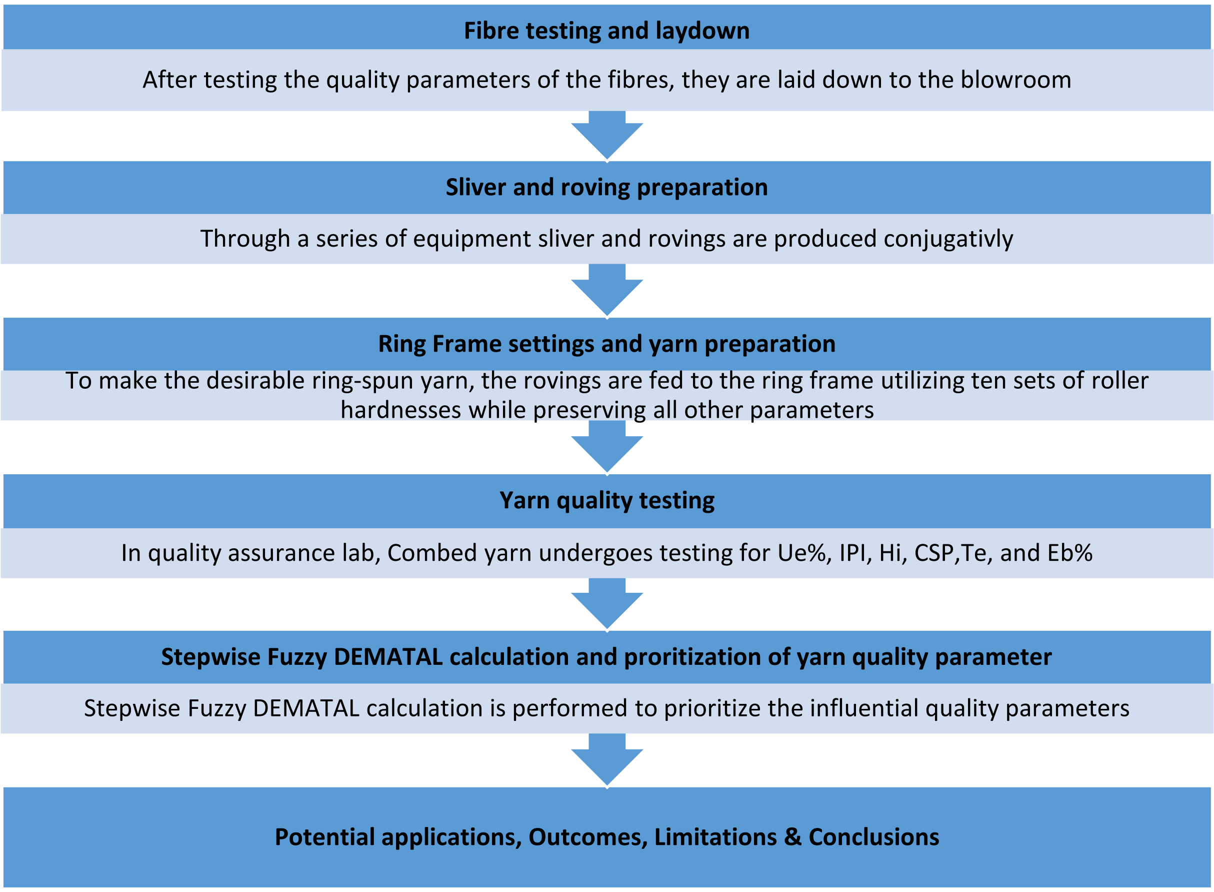

Figure 2. Detailed framework of the research

Methodology of Data Organization

Initially, the study began with the identification of several qualitative attributes. Subsequently, researchers and business leaders from the business involved performed face-to-face interviews addressing the findings. Table 1 provides details regarding the individuals who are a part of this committee. Significant characteristics of quality were discovered as a result of those interactions. After that, every single thing that was discovered through extensive investigation was evaluated with the assistance of these experts' extensive experience in the real-life environment. Fuzzy DEMATEL offers a methodical and well-informed approach to investigating yarn quality issues. This approach is founded on research findings and specialists' evaluations, which provide its core foundation [24].

Table 1. The professional group participant's details

Total Participants	Positions	Skills	Experiences (years)
15	Chief Quality Officer, Senior Quality Manager, Distinguish Professor, Associate and Assistant Professor	Yarn Quality Control and analytics of data	8-30

RESULTS

Details step-by-step calculations for Fuzzy DEMATEL Methodology

Fuzzy DEMATEL is a comprehensive approach to evaluating complicated structures with interconnected and interrelated parts. It combines fuzzy logic with the DEMATEL method. The Fuzzy DEMATEL procedure's computations are laid forth below in a comprehensive, step-by-step technique:

First step: Identification of the criteria

Before beginning the study, we must choose what we want to investigate and catalogue every part of the system that impacts it. For example, this study analyzed six quality criteria for the combed ring-spun yarn. The criteria are Ue%, IPI, Hi, CSP, Te, and Eb%.

Second step: Constructing a matrix of Direct Relationships

Experts are expected to evaluate the impact of one criterion on another by drawing parallels between the two. It is common practice to use a scale such as "0 stands for no influence", "1 stands for minor influence", "2 stands for medium influence," and "3 stands for major influence" when making such comparisons [20]. The findings are displayed in a matrix (See Table 2).

Table 2. Development of Straight Correlation Matrix

	Ue	IPI	Hi	CSP	Te	Eb	Sum
Ue	0	3	1	3	3	1	11
IPI	3	0	2	3	3	2	13
Hi	1	1	0	2	3	2	9
CSP	3	2	0	0	3	2	10
Te	2	1	1	3	0	1	8
Eb	0	2	1	2	2	0	7

Third step: Straight Correlation Matrix Normalisation Process

Each Straight Correlation Matrix element is normalized to a value between 0 and 1 by dividing by the greatest possible sum of rows in the matrix [22] by the below formula (1) (see Table 3). These values are called crips values.

$$S_{xy} = \frac{B_{xy}}{\sum_1^m B_{xy}} \tag{1}$$

Here, S= Normalized Straight Correlation Matrix, x and y represent the number of rows and columns respectively, and m represents the number of criteria.

Table 3. Normalisation Process of Direct Relationship Matrix

	Ue	IPI	Hi	CSP	Te	Eb
Ue	0	0.23	0.076	0.23	0.23	0.076
IPI	0.23	0	0.153	0.23	0.23	0.153
Hi	0.076	0.076	0	0.153	0.23	0.153
CSP	0.23	0.153	0	0	0.23	0.153
Te	0.153	0.076	0.076	0.23	0	0.076
Eb	0	0.153	0.076	0.153	0.153	0

Fourth step: Overall Correlation Matrix (R) Calculation

The Overall Correlation Matrix (R) incorporates the cascading or indirect implications of criteria on one another due to their interrelations, going beyond the Straight Correlation Matrix in its ability to capture the direct impacts between criteria [23]. See the attached Table 4 for details.

It's derived using the formula: R=S_{xy}A(L−S_{xy})$^{-1}$

Where:

R is the Overall Correlation Matrix.

S_{xy} is the Normalized Straight Correlation Matrix.

L is the Identity Matrix.

The inverse of L–S_{xy} is represented by (L–S_{xy})$^{-1}$.

Table 4. Development of Overall Correlation Matrix (R)

	Ue	IPI	Hi	CSP	Te	Eb
Ue	0.4532	0.5964	0.2929	0.7597	0.7781	0.4219
IPI	0.6841	0.4574	0.3794	0.8263	0.8500	0.5241
Hi	0.4049	0.3793	0.1682	0.5683	0.6415	0.4032
CSP	0.5909	0.5060	0.2103	0.5169	0.7170	0.4411
Te	0.4636	0.3766	0.2271	0.6087	0.4359	0.3299
Eb	0.2968	0.3868	0.2138	0.4948	0.5082	0.2288

Fifth step: Find the Values of Cause and Effect

Cause (C_i): Total row values of Overall Correlation Matrix R, representing a criterion's total effect on all other criteria.

Effect (E_i): Total column values of Overall Correlation Matrix R, showing how much a criterion is affected by all other criteria [22].

The obtained values of Causes and Effects are demonstrated in below Table 5.

Table 5. Values of Cause and Effect

	Ue	IPI	Hi	CSP	Te	Eb	C_i
Ue	0.4532	0.5964	0.2929	0.7597	0.7781	0.4219	3.3022
IPI	0.6841	0.4574	0.3794	0.8263	0.85	0.5241	3.7213
Hi	0.4049	0.3793	0.1682	0.5683	0.6415	0.4032	2.5654
CSP	0.5909	0.506	0.2103	0.5169	0.717	0.4411	2.9822
Te	0.4636	0.3766	0.2271	0.6087	0.4359	0.3299	2.4418
Eb	0.2968	0.3868	0.2138	0.4948	0.5082	0.2288	2.1292
E_i	2.8935	2.7025	1.4917	3.7747	3.9307	2.349	

Sixth step: Find the Values of Prominence

For each criterion, determine:

Prominence (C_i+E_i): Prominence is a significant term that is the sum of the total influences given and received by a criterion. By seeing the correlation among the criteria, it is easier to find out the factors that are driving change and those that are merely responding to it [23]. For details see the attached Table 6.

Table 6. Values of Prominence

	C_i	E_i	C_i+E_i
Ue	3.3022	2.8935	6.1957
IPI	3.7213	2.7025	6.4238
Hi	2.5654	1.4917	4.0571
CSP	2.9822	3.7747	6.7569
Te	2.4418	3.9307	6.3725
Eb	2.1292	2.349	4.4782

Seventh step: Results analysis and decision-making

Applying the prominence values and the cause-and-effect diagram, evaluate the connections between the criteria. Sort the criteria by how crucial they are to the overall system. This helps decision-makers zero in on the most pressing issues and causes [24]. From the prominence values obtained in above Table 6, it is observed that CSP and IPI are the most influential quality parameters that affect the other quality parameters. On the other hand, hairiness is the least influential which is dominated by other parameters.

Results Obtained by Testing the Produced Yarns in the Quality Assurance Laboratory

Table 7. Obtained data for the Quality Parameters

Sl No.	Roller Hardness (Back/ Front)	Ue%	IPI	Hi	CSP	Te	Eb%
1	83/83	10.12	113.4	4.12	2402.56	18.69	3.33
2	83/80	9.34	79.7	3.57	2431.22	19.78	4.07
3	83/75	9.13	71.7	3.4	2445.73	19.64	3.97
4	83/70	9.2	80.2	3.45	2460.8	20.06	3.92
5	75/75	8.5	65.3	3.22	2517.80	21.14	4.01
6	65/83	9.7	98.3	3.98	2413.32	20.63	3.55
7	70/83	9.52	87.5	3.83	2423.3	19.88	3.78
8	75/83	9.35	77.1	3.67	2445.32	19.91	3.95
9	80/83	9.54	101.3	4.1	2440.4	18.88	3.49
10	65/65	10.1	118.5	4.21	2391.12	18.5	3.54

DISCUSSIONS

Unevenness

Consider making the rollers harder for better fibre grip, constant alignment, and even less yarn unevenness. A yarn with an uneven diameter and a more significant irregularity could result from excessive stretching or damaging of the fibres in the yarn. On the other hand, if the hardness is reduced, there may be inadequate fibre control, which could result in thicker and more inconsistently woven yarn. Lessening the possibility of fibre damage with softer rollers may also increase the likelihood of fibre sliding, exacerbating unevenness [40]. Improving the unevenness characteristics of combed woven yarn requires finding a suitable drafting roller hardness [6]. All the values of unevenness are shown in Table 7.

Imperfection Index

Increasing the roller's hardness typically results in a better grip on fibres, which improves yarn uniformity and reduces initial flaws. However, there is a limit beyond which increased hardness can damage fibres, causing additional noticeable thick and thin variations and a higher imperfection index [6]. The roller's ability to hold on to fibres decreases as hardness decreases. As a result, there is a greater probability of uncontrolled alignment and drafting, contributing to the total number of flaws [41]. A softer roller may reduce the occurrence of neps because of its milder impact on the fibres, but this may harm the quality of the yarn. Therefore, adjusting roller hardness is crucial to achieving a pleasing equilibrium in yarn defects [39].

Hairiness

Hairiness is a significant criterion for combed yarn quality which is greatly influenced by the drafting roller hardness. Increasing the roller's hardness can enhance fibre grip, reducing fibre protrusions and minimizing hairiness in the yarn. However, when the degree of hardness is too high, fibre damage can occur, perhaps resulting in increased hairiness due to broken or misaligned fibres. In contrast, insufficient fibre control might occur when hardness is decreased. This slipperiness could allow more fibres to emerge from the yarn's centre, increasing its hairiness. Softer rollers prevent fibres from being damaged as severely, but they can also encourage hairiness if they fail to hold the fibres in place tightly enough [42]. Maintaining command over the hairiness characteristics of combed woven yarn causes a roller hardness adjustment [12].

Count Strength Product (CSP)

A greater CSP can be achieved by increasing the roller's hardness, which improves fibre gripping and yarn strength. The amount of CSP it can hold is impacted negatively if the hardness is increased beyond a safe point. Reducing the roller's hardness may result in uneven fibre drafting due to decreased grip [12]. Because of this, the CSP may suffer in areas where the yarn is weakened. Using softer rollers may be friendlier on the fibres and the yarn, which could help preserve its strength [43]. However, this may also lead to irregularity in the drafting process, which makes it more challenging to keep a high CSP. As a result, getting desirable CSP values depends critically on adjusting roller hardness [5].

Tenacity

Increasing the roller's hardness can improve fibre grip, improving the yarn's strength [2]. However, If the hardness increases too much, the yarn's fibres may break, reducing the yarn's strength. If the roller hardness is decreased, less control is exercised over the fibres, and the yarn's structure may become inconsistent [12]. Because weakened areas of the yarn tend to grow more commonly with variation, this may reduce the yarn's strength. Softer rollers are better for the fibres since they preserve the fibres' natural strength, but they also allow for more erratic drafting, which weakens the yarn [44]. The strength of combed yarn is increased by adjusting the rollers to a middle hardness [6].

Elongation at Break

An improved grip on the fibres, which may result in a more even yarn with improved elongation qualities, is one effect of increasing the hardness [5]. The yarn's ability to stretch before breaking could be reduced if treated to too high hardness levels, which could cause unnecessary tension or fibre damage. On the other hand, yarn produced with softer rollers, with less hardness, may exhibit uneven elongation attributes because of less uniform fibre alignment [45]. The risk of breaking is reduced when fibres get handled more gently by softer rollers; however, this consistency is necessary for optimal Elongation. Elongation at break is essential for combed woven yarn, which can only be attained by using rollers with the correct balance of hardness [39].

Key Findings

There's a vital relationship between the drafting roller hardness and combed yarn quality. As the hardness increased to a specific limit, certain yarn quality metrics, such as unevenness and imperfection, were, but those values deteriorated after a particular increase in hardness.

Like unevenness values, single and bundle yarn strength and Elongation properties show the same trend. Yarn tensile properties are also dependent on the suitable settings of roller hardness.

From Fuzzy DEMATEL analysis, it is also obtained that tensile properties with imperfections values are the most influential quality parameters which are also in line with the requirements for the combed yarn. It is also obtained that hairiness is the least significant as for the combed yarn which values are the least.

Limitations

- The study focuses explicitly on drafting roller hardness, potentially overlooking other significant factors affecting yarn quality, such as spindle speed, spacer size, etc.
- This study primarily applies to the specific fibre types; results might differ from other materials.

- Testing scenarios might not account for variations in ambient conditions, like humidity and temperature, which significantly affect spinning.

CONCLUSION

The findings of this study concerning how the hardness of drafting rollers affects the quality of combed yarn spun on a ring frame are crucial to the yarn manufacturing industry. From this study, it is also clear that one of the most significant variables in determining the quality of cotton combed ring-spun yarns is the hardness of the drafting roller. Up to a certain level of hardness, it is shown that yarn uniformity improves, resulting in a significant reduction in unevenness (Ue%). Common imperfections of yarns are significantly decreased by this particular hardness setting. Similarly, the yarn strength and elongation properties also parallel the trends observed in roller hardness modifications, highlighting the need to get the balance right. The research pinpointed the ideal range of hardness for drafting rollers that reliably generate high-quality yarns. Because of this, mills that want to raise the quality of their yarn to meet stringent industry standards must carefully adjust the hardness of their drafting rollers. The use of the DEMATEL methodology also indicates the quality parameters such as imperfections and both single and bundle strength values that need to be prioritised by real-life practitioners for producing the highest quality yarns.

Author Contributions

Conceptualization – Raian S; formal analysis – Hossen J, Saha SK, and Khan SQ; investigation – Haque E and Raian S; resources – Saha SK, Khan SQ, Hossen J, and Haque E; writing-original draft preparation – Raian S, Saha SK, Hossen J, and Haque E; writing-review and editing – Saha SK, Hossen J, Haque E; visualization – Saha SK, Hossen J, Haque E, Hossain KR; supervision – Saha SK, Hossen J, Haque E, Hossain KR. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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