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Effect of bottom front roller eccentricity on yarn unevenness (U%), mass variation (CV%), and hairiness in PV 30 ring spinning

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ABSTRACT
This study demonstrates that bottom front roller eccentricity in ring spinning negatively affects PV 30 yarn quality by increasing yarn unevenness (U%) and mass variation (CV%). Using a paired-sample experimental design and paired t-test analysis, the study evaluated yarn quality before and after corrective alignment of the bottom front roller under controlled mechanical and environmental conditions. Yarn unevenness decreased from 9.43 ± 0.20 to 8.55 ± 0.06, while yarn mass variation decreased from 11.87 ± 0.30 to 10.76 ± 0.10 after corrective alignment, indicating statistically significant improvements in drafting stability and yarn uniformity ($p < 0.05$) with a large practical effect size based on Cohen's d analysis (Cohen's $d = 1.21$). The bottom front roller was specifically investigated because it directly controls fiber movement within the drafting zone, where mechanical instability can generate irregular fiber tension and drafting waves. In contrast, no statistically significant effect on yarn hairiness was observed. From an industrial engineering perspective, the findings highlight the importance of preventive maintenance and precise roller alignment in reducing off-quality yarn production, minimizing material waste, and improving operational efficiency. Unlike previous studies that broadly examined drafting irregularities and machine vibration, this study specifically isolates the effect of bottom front roller eccentricity before and after corrective alignment under controlled operating conditions.

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1. INTRODUCTION

The quality of spun yarn is a fundamental determinant of textile product performance [1]. Key quality parameters such as yarn unevenness (U%), coefficient of mass variation (CV%), and hairiness directly affect both manufacturing efficiency and the physical properties of the resulting fabric [2], [3]. Among various production stages, ring spinning is especially sensitive to mechanical precision, with the drafting zone serving as a crucial point for fiber alignment and attenuation precision [4], [5]. Regarding the operational integrity of spinning machinery, the condition of the bottom front roller is particularly crucial for maintaining yarn consistency [6].

In recent years, the textile industry has increasingly adopted predictive maintenance and Total Productive Maintenance (TPM) strategies to improve operational efficiency, reduce unplanned downtime, and optimize product quality [7], [8]. The integration of advanced monitoring technologies has improved the effectiveness of predictive maintenance in spinning and weaving operations [9]. Recent studies have highlighted the growing importance of IoT-based predictive maintenance systems in improving operational efficiency in textile manufacturing [10], [11]. Simi et al. [12] reported that predictive maintenance systems reduced equipment failures and maintenance costs in textile machinery. Similarly, Ozek et al. [13] reported that TPM implementation in textile factories led to measurable improvements in machine utilization and yarn quality.

Gope [14] also demonstrated the effectiveness of AI-based predictive maintenance in improving spinning machine reliability and product consistency. In addition, Tsai et al. [15] examined the integration of Industry 4.0 technologies, including real-time sensing and ERP systems, into a sustainable production framework for the textile industry. These developments underscore the critical role of predictive and total productive maintenance in driving the competitiveness and sustainability of modern textile operations.

The relationship between mechanical imperfections and yarn quality has been well established [16]. Recent studies have demonstrated that factors such as roller misalignment, bearing wear, and eccentric rotation can significantly increase yarn unevenness and mass variability [6], [17], [18]. Mechanical defects in drafting components may disrupt fiber control during attenuation, resulting in drafting instability, irregular fiber tension, and non-uniform yarn structure. However, most prior research has predominantly addressed macro-level influences such as fiber blend ratios and spindle speeds [19], [20], while the effects of discrete mechanical imperfections within the drafting system remain insufficiently quantified under controlled experimental conditions. Investigations specifically quantifying the influence of roller alignment on U%, CV%, and hairiness remain scarce [21], [22]. Most previous studies evaluated drafting defects collectively, making it difficult to determine the direct contribution of bottom front roller eccentricity to yarn quality deterioration

Among drafting system components, the bottom front roller plays a particularly critical role because it directly governs fiber movement and tension distribution in the final drafting zone prior to twist insertion [6]. Any eccentricity in this roller may generate periodic drafting waves, unstable fiber control, and uneven mass distribution along the yarn length, thereby deteriorating yarn quality parameters [23]. Despite its practical importance in industrial ring spinning operations, the isolated effect of bottom front roller eccentricity has received limited experimental attention [24].

Despite the extensive body of literature on yarn quality and maintenance strategies in ring spinning systems, the specific influence of bottom front roller eccentricity on yarn quality parameters remains insufficiently understood. Previous studies have predominantly focused on macro-level variables such as fiber blend composition, spindle speed, or general maintenance practices, while discrete mechanical imperfections within the drafting system have rarely been isolated as independent experimental variables [25]–[28]. In addition, many previous investigations evaluated machine conditions qualitatively or collectively without experimentally comparing yarn quality before and after corrective mechanical alignment under controlled conditions [29]–[31]. To the best of our knowledge, no prior study has quantitatively examined bottom front roller eccentricity as a single controlled factor using a paired-sample experimental design under strictly regulated mechanical and environmental conditions. To address these limitations, this study provides a more direct and experimentally controlled evaluation of bottom front roller eccentricity than previous studies reported in the literature.

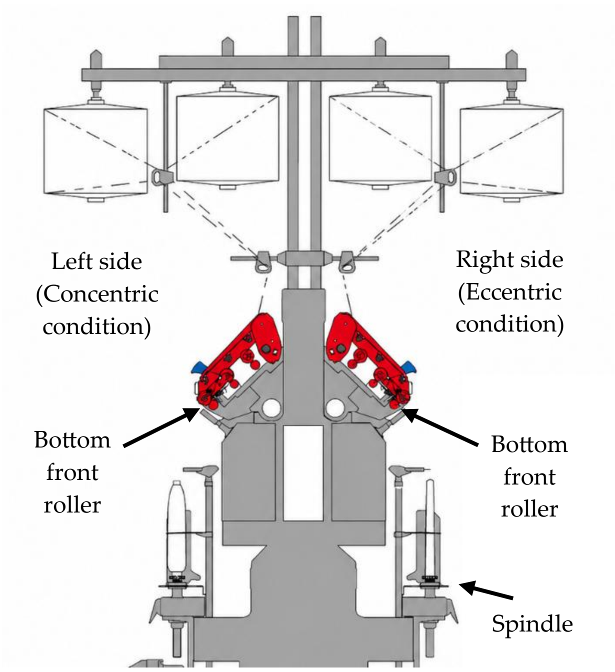
Therefore, the primary objective of this study is to quantitatively assess the effect of bottom front roller eccentricity on critical yarn quality parameters, namely yarn unevenness (U%), coefficient of mass variation (CV%), and hairiness, in PV 30 yarns, which are widely used in woven and knitted fabric applications and require high uniformity for stable industrial production. Using a paired-sample experimental design and statistical effect size analysis (Cohen’s d), this study aims to provide empirical evidence supporting maintenance optimization and yarn quality improvement in ring spinning operations.

2. MATERIALS AND METHODS

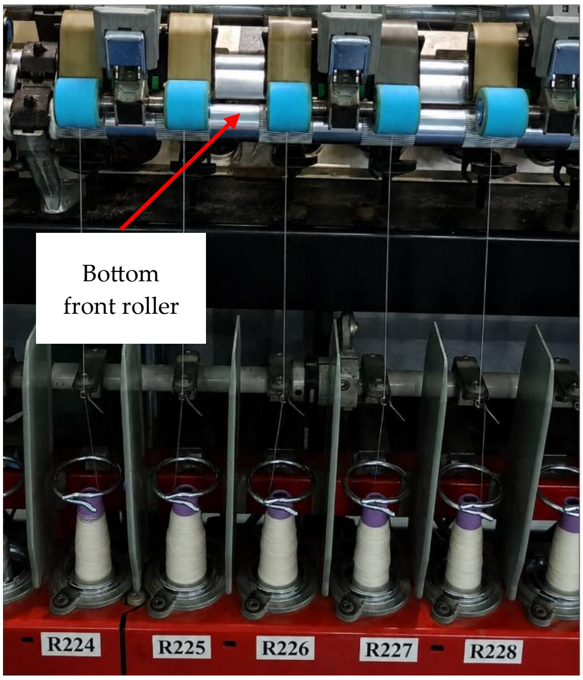
This study employed a quantitative experimental design to examine the effects of bottom front roller eccentricity on yarn unevenness (U%), mass variation (CV%), and hairiness. Experiments were performed using a Toyoda RY ring spinning machine (manufactured in 1982) at PT Dan Liris, lane F, machine 19. The machine processed PV 30 yarn and Ne 1.09 sliver roving. All material input and machine settings were kept constant to ensure comparability [3], [17].

Two machine conditions were evaluated: eccentric and concentric alignment of the bottom front roller. Eccentricity was measured using a dial indicator with 0.01 mm precision. In the eccentric state, deviation reached 0.12 mm, exceeding the ±0.05 mm allowable range. The eccentricity level of 0.12 mm was selected because it represented the actual mechanical deviation detected in the industrial spinning machine during routine maintenance inspection. This value was considered sufficient to produce measurable drafting instability while still reflecting realistic operating conditions commonly encountered in industrial ring spinning systems. Following realignment and neck bearing replacement, deviation was reduced to below 0.02 mm, confirming concentricity [21]. To ensure that these two conditions could be validly compared, careful spindle selection and preparatory procedures were subsequently implemented.

Ten spindles located symmetrically on the same machine section were selected and assigned to two paired conditions based on spindle position. Five right-side spindles (R224, R225, R226, R227, and R228) were operated under the eccentric bottom front roller condition, while five corresponding left-side spindles (L224, L225, L226, L227, and L228) were operated under the concentric condition after mechanical realignment. Each left–right spindle pair (e.g., R224–L224) was treated as a matched experimental pair, ensuring that both conditions were exposed to identical machine settings and environmental conditions, apart from roller eccentricity. The experimental arrangement and the bottom front roller configuration investigated in this study are presented in Figure 1.



(a)



(b)

(c)

Figure 1. Experimental setup consisting of (a) schematic paired bottom front roller positions [32], (b) experimental spindle section, and (c) bottom front roller component similar to that used in the experiment [33].

Prior to experimentation, all selected spindles were verified to be in uniform mechanical condition. Verification was conducted through runout tolerance measurement using a dial gauge, with acceptable deviation defined as ≤0.02 mm, and by confirming the absence of visible bearing wear. This purposive and paired spindle selection approach enhanced internal validity by minimizing variability arising from spindle position and mechanical wear. However, the absence of randomization may introduce selection bias and limit external validity. This was a methodological decision prioritizing precision and control, while future studies may consider randomized spindle selection to broaden generalizability.

The required sample size was determined through a priori power analysis using SPSS (v27). The analysis ensured 80% statistical power to detect a medium effect size (Cohen's d = 0.5) at $\alpha = 0.05$, consistent with best practices in experimental textile engineering [34]–[36]. Based on this calculation, 40 yarn samples were collected from each roller condition, resulting in a total of 80 yarn samples. A total of 40 yarn samples were collected using a paired sampling strategy, in which yarns produced under eccentric and corrected roller conditions were obtained from matched spindle positions operating under identical machine and environmental conditions.

Before data collection, the machine underwent comprehensive cleaning and inspection. All lint and residue were removed, lubrication was refreshed, and the system was run to steady-state operation. Yarn was then wound under controlled tension onto standard bobbins, labeled, and stored in sealed containers to prevent environmental contamination [6]. Representative yarn samples produced from the left-side and right-side bottom front roller positions are shown in Figure 2. The upper image represents the yarn sample produced from the left-side bottom front roller position, while the lower image represents the yarn sample produced from the right-side bottom front roller position. With these preparatory steps completed, the yarn samples were ready for systematic testing.

Figure 2. Representative PV 30 yarn samples produced under eccentric and concentric roller conditions.

All samples were tested individually using Uster Tester 6 [37], which is widely recognized for its reliability in assessing U%, CV%, and hairiness in staple yarn [3]. Test settings were as follows: 800 meters per minute, 1.25 minutes duration, and 1,000 meters sample length. Descriptive statistics (mean, standard deviation) were calculated for each variable. Prior to conducting the paired-sample t-test, the data were screened for potential outliers using boxplot visualization and assessed for normality to ensure the appropriateness of parametric statistical analysis. No extreme outliers were identified in the dataset. Paired sample t-tests were performed to compare eccentric versus concentric conditions, with matching explicitly based on corresponding left–right spindle positions [22], [36]. Statistical significance was set at $p < 0.05$.

Testing was conducted from March to June 2025 under controlled environmental conditions of 26–28°C and 58–62% RH, monitored with a calibrated Testo 608-H2 thermo-hygrometer [20]. To minimize confounding, all experiments were restricted to a single machine and lane, thereby maximizing internal validity but limiting external generalizability [38], [39]. While the study design maximized control over mechanical and environmental factors, its narrow scope means the results may not extrapolate to other machine models, fiber blends, or industrial settings without further validation [36].

3. RESULTS

This study aimed to investigate the effect of bottom front roller eccentricity on yarn quality, focusing on three key parameters: unevenness (U%), coefficient of mass variation (CV%), and hairiness. The variables analyzed describe yarn quality under two conditions: eccentric (Ecc) and concentric (Conc), using 40 observations per condition. Each pair of variables corresponds to one measurement in each condition.

UEcc and UConc represent the yarn unevenness (U%). This index measures the uniformity of mass distribution along the yarn, where a lower value indicates greater consistency. CVEcc and CVConc refer to the coefficient of variation (CV%) of the yarn mass, reflecting the relative variability in yarn thickness. HairEcc and HairConc represent the hairiness index of the yarn, which measures how many fiber ends protrude from the yarn surface. These three metrics (U%, CV%, and hairiness) are standard indicators of yarn performance and are essential in assessing the quality and stability of yarn production.

3.1. Descriptive Statistics

The descriptive statistics of U%, CV%, and hairiness for both conditions are provided in Table 1. The mean value of U% under the eccentric condition is higher than under the concentric condition (9.43 vs. 8.55), indicating increased unevenness in that setting. A similar pattern is observed for CV%, where the mean under eccentric is 11.87, compared to 10.76 under concentric. Hairiness showed similar means under both conditions.

Table 1. Sample Yarn Quality Data: U% (unevenness in %), CV% (coefficient of variation in %), Hairiness (index)

Variable	N	Mean	Std. Deviation
UEcc	40	9.43	0.20
UConc	40	8.55	0.06
CVEcc	40	11.87	0.30
CVConc	40	10.76	0.10
HairEcc	40	5.08	0.13
HairConc	40	5.08	0.14

Furthermore, the observed difference in hairiness is statistically non-significant and should not be interpreted as a causal effect. These results suggest that yarn evenness and variability are more sensitive to machine eccentricity than hairiness. Standard deviations are presented in Table 1 to indicate variability. However, confidence intervals were also calculated to improve interpretability. The 95% confidence interval for UEcc ranged from 9.36 to 9.49, and for UConc from 8.53 to 8.57. Similar ranges were computed for CV% and hairiness.

3.2. Normality Assessment via Shapiro–Wilk Test

To evaluate the assumption of normality for each variable, the Shapiro–Wilk test was conducted due to its robustness for small to moderate sample sizes. Table 2 presents the Shapiro–Wilk statistics and their corresponding p-values for each of the six variables under investigation.

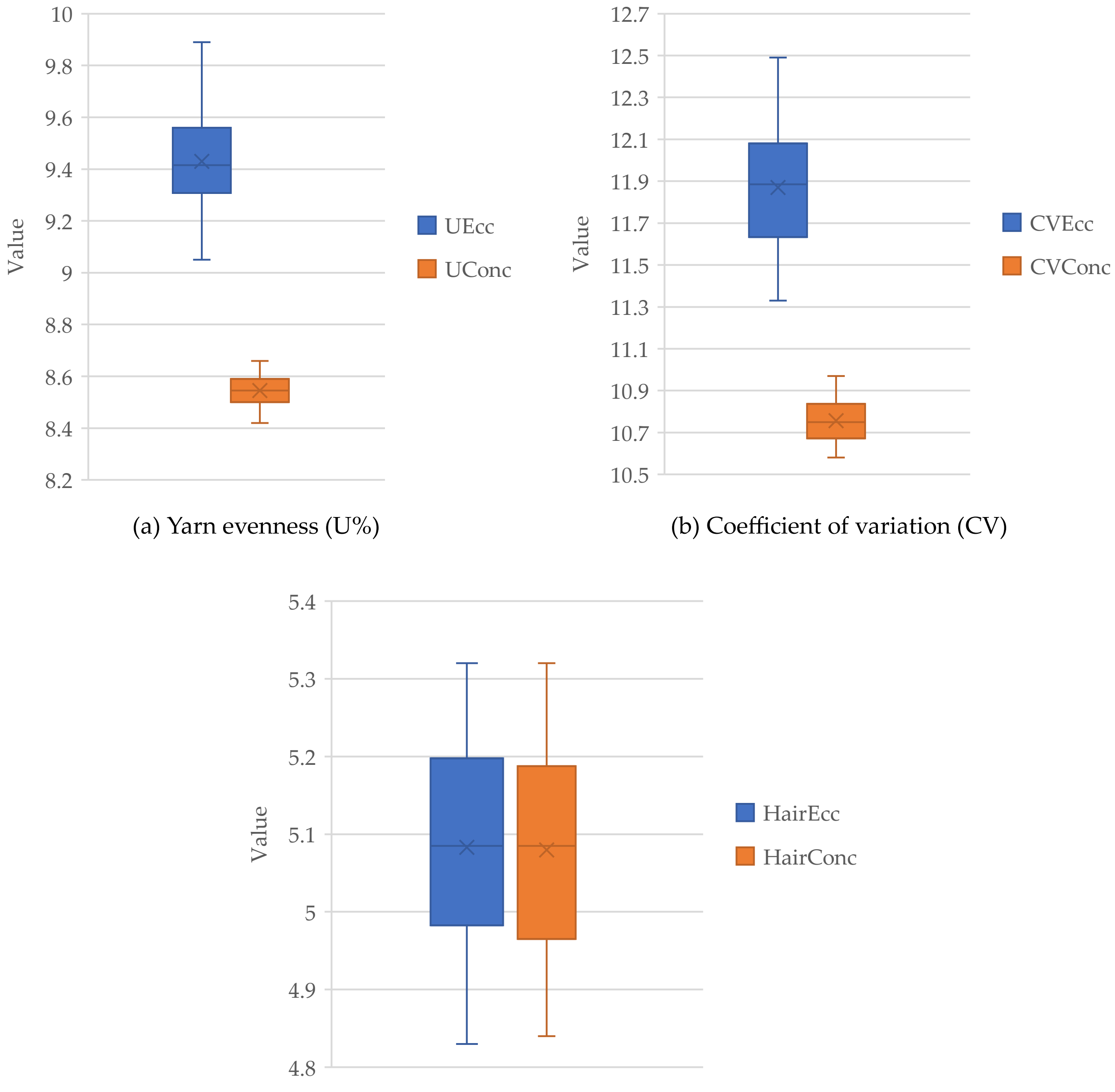
Table 2. Shapiro–Wilk Normality Test Results

Variable	Shapiro–Wilk Statistic	df	*p*-value
UEcc	0.987	40	0.918
UConc	0.987	40	0.908
CVEcc	0.979	40	0.635
CVConc	0.976	40	0.555
HairEcc	0.975	40	0.514
HairConc	0.968	40	0.319

As observed, all p-values are well above the conventional alpha level of 0.05, indicating no significant departure from normality in any of the variables. Consequently, the null hypothesis of normal distribution cannot be rejected for any of the measured constructs. These results support the assumption of normality, thus validating the application of parametric statistical procedures in the subsequent analyses. Residuals from the paired differences were also examined. Visual inspection indicated approximate symmetry and absence of major outliers. This supports the use of the paired t-test without additional transformation.

3.3. Box Plot Visualization

To complement the numerical results, Figure 3 presents box plots of U%, CV%, and hairiness for eccentric and concentric bottom roller conditions. The visualization highlights clear increases in both the median and spread of yarn unevenness and mass variation with eccentric rollers, while hairiness remains largely unaffected. These visual patterns are consistent with the statistical analyses, confirming that eccentricity primarily impacts mass distribution and uniformity, not surface fiber protrusion.



(a) Yarn evenness (U%)

(b) Coefficient of variation (CV)

(c) Yarn hairiness

Figure 3. Box plots of yarn quality parameters under eccentric (Ecc) and concentric (Conc) bottom front roller conditions.ity parameters under eccentric (Ecc) and concentric (Conc) bottom front roller conditions.

According to Figure 3, yarn unevenness (U%) shows a higher median and greater spread in the eccentric setting than in the concentric setting. Coefficient of mass variation (CV%) also exhibits increased central tendency and variability under eccentric conditions. Hairiness index distributions are similar for both roller alignments, indicating minimal influence of eccentricity. Each box shows the interquartile range, the line within the box indicates the median, and whiskers denote the full data range (excluding outliers).

3.4. Paired Samples T-Test Results

Given the normality assumption and the study's paired design, a paired-samples t-test was used to determine whether the differences between the eccentric and concentric conditions were statistically significant. The results are summarized in Table 3. The results show that the mean U% was significantly higher under the eccentric condition compared to the concentric condition (M = 0.88, t(39) = 27.19, p < 0.001). This indicates a substantial increase in yarn unevenness due to roller eccentricity.

Table 3. Paired Samples T-Test Results

Yarn Quality Parameter	Mean Diff. (Ecc - Conc)	95% CI for Diff.	*t*	*df*	*p*
U%	0.88	[0.82, 0.95]	27.19	39	< 0.001**
CV%	1.11	[1.02, 1.21]	23.88	39	< 0.001**
Hairiness	0.003	[–0.05, 0.06]	0.12	39	0.909

** p < 0.001; ns: not significant (p > 0.05)

Similarly, CV% also showed a statistically significant increase under eccentric conditions (M = 1.11, t(39) = 23.88, p < 0.001). This suggests that eccentricity in the bottom front roller leads to greater variation in yarn mass. In contrast, there was no statistically significant difference in hairiness between the two conditions (M = 0.003, t(39) = 0.12, p = 0.909). The confidence interval for the difference includes zero, further confirming that hairiness was not affected by the roller alignment. Given the negligible effect size and wide confidence interval, a Type II error cannot be ruled out; future studies with larger sample sizes may be warranted to confirm these findings [34], [40]. These results confirm that roller eccentricity significantly affects yarn linearity and mass variation, while its effect on hairiness remains inconclusive.

3.5. Effect Size Analysis

Effect sizes were calculated using Cohen's d and Hedges' correction for paired samples [16]. Using SPSS Statistics version 27 (IBM Corp.) and standard formulas for dependent (paired) data , we computed effect sizes and their 95% confidence intervals. These metrics quantify the standardized magnitude of mean differences. Table 4 summarized the results.

Table 4. Standardized Effect Sizes for Paired Comparisons

Comparison	Effect Size (d)	95% CI Lower	95% CI Upper	Interpretation
UEcc vs. UConc	4.30	3.30	5.29	Very large
CVEcc vs. CVConc	3.78	2.88	4.66	Very large
HairEcc vs. HairConc	0.02	–0.29	0.33	Negligible

The effect size for U% was 4.30, indicating a very large impact of eccentricity on yarn evenness. Similarly, CV% showed a very large effect size of 3.78, confirming practical significance in mass variability. In contrast, hairiness had an effect size of only 0.02, with a confidence interval crossing zero, indicating a negligible and statistically uncertain effect. These findings confirm that mechanical eccentricity significantly influences yarn structure, but not surface fibre protrusion.

4. DISCUSSION

This study confirmed that bottom front roller eccentricity significantly increased yarn unevenness and mass variation, but had no significant effect on yarn hairiness. Both increases in U% and CV% were statistically robust and practically meaningful. The observed effect sizes (Cohen's d > 3.7) indicate a strong influence of mechanical alignment on yarn consistency in ring spinning systems, highlighting the critical role of roller concentricity in maintaining drafting stability.

These exceptionally large effect sizes are uncommon in textile research and can be attributed to the rigorously controlled experimental conditions employed in this study, where a single machine, homogeneous materials, and stable ambient conditions minimized random and extraneous variability. By isolating bottom front roller eccentricity as a single controlled variable, this study directly quantified its mechanical impact without interference from other drafting-related factors. Prior studies have typically examined roller geometry alongside multiple sources of mechanical and process variability, limiting the precision of causal interpretation [41]. The present design resulted in very low within-pair standard deviations, thereby amplifying the observable contrast between eccentric and concentric roller conditions. However, under typical industrial environments with higher process variability, the magnitude of these effects may be reduced, although the practical relevance is expected to remain significant [36], [42].

These findings support earlier work by [1], which linked roller geometry to drafting uniformity. However, unlike previous studies, the present work isolates roller axis misalignment as the sole experimental factor under tightly controlled mechanical and environmental conditions. This experimental approach strengthens the causal interpretation of the relationship between bottom front roller eccentricity and yarn quality deterioration. This provides direct empirical evidence that roller eccentricity alone is sufficient to produce substantial degradation in yarn mass uniformity, thereby strengthening the mechanistic understanding of drafting instability in ring spinning systems.

The observed increases in yarn unevenness and mass variation under eccentric roller conditions are also consistent with previous studies investigating drafting instability caused by roller misalignment, bearing wear, spindle vibration, and eccentric rotation [6], [17], [18]. Earlier research reported that mechanical irregularities within the drafting system can disrupt fiber control, generate fluctuating drafting tension, and increase yarn mass irregularity [16], [23].

The trends observed in the present study are therefore comparable to those reported in the literature [6], [17], although the magnitude of the observed effects appears larger due to the highly controlled experimental design and the isolation of bottom front roller eccentricity as a single independent variable. Unlike studies that evaluated multiple machine-related disturbances simultaneously, the present work directly quantified the specific contribution of bottom front roller eccentricity under controlled operating conditions.

Mechanistically, eccentric roller rotation may generate periodic drafting waves and unstable fiber tension distribution, leading to non-uniform fiber attenuation and increased yarn mass irregularity [16], [23]. This suggests that even localized mechanical deviations within the drafting system may substantially affect yarn uniformity and process stability.

In contrast to yarn unevenness and mass variation, hairiness was unaffected by bottom front roller eccentricity. This observation aligns with prior studies suggesting that surface fiber protrusion is more strongly influenced by frictional interactions, fiber properties, and aerodynamic effects than by drafting precision [34], [21]. Although the observed effect size for hairiness was negligible, the wide confidence interval suggests that small effects cannot be entirely ruled out. Therefore, the possibility of a Type II error cannot be ruled out, particularly given the moderate sample size employed in this study [34], [35]. Future investigations with larger datasets or meta-analytic approaches may be required to conclusively determine whether subtle effects of roller eccentricity on hairiness exist.

The experimental setup prioritized strict mechanical and environmental control by using a single machine, a single yarn type, and a fixed eccentricity threshold. While this approach enhanced internal validity and enabled precise causal inference, it limits direct generalization to other spinning machines, fiber blends, or operating conditions. Additionally, using a single eccentricity level does not capture the full range of mechanical wear commonly encountered in industrial settings. Future research should therefore investigate multiple eccentricity levels across different machine models and material compositions to better represent real-world production variability and improve external validity.

From an industrial engineering perspective, the ability to isolate and quantify the effect of a single source of drafting instability underscores the importance of precise mechanical alignment in preventive maintenance strategies. Realigning bottom front rollers can reduce yarn defects, improve uniformity, and lower waste rates in production.

In industrial weaving and knitting operations, increased yarn unevenness and mass variation may contribute to higher yarn breakage rates, reduced weaving efficiency, fabric defects, and increased rejection rates, ultimately leading to additional material waste and production costs. Therefore, maintaining roller concentricity is important not only for yarn quality but also for downstream manufacturing performance and process reliability [43], [44].

Routine eccentricity inspection using simple dial indicators is a low-cost, potentially high-impact maintenance intervention for ring spinning operations.

The present findings also support the integration of predictive maintenance and Industry 4.0 approaches in textile manufacturing. Real-time monitoring systems and sensor-based diagnostics may enable early detection of roller misalignment before significant yarn quality deterioration occurs. Such systems may also improve maintenance scheduling, reduce unplanned downtime, and enhance operational decision-making in smart textile production environments [45], [46].

While the present findings are based on controlled experimental conditions, they suggest that preventive alignment checks may be broadly applicable for improving process stability and operational efficiency in industrial ring spinning systems.

Furthermore, preventive alignment maintenance may contribute to sustainability objectives by reducing off-quality yarn production, minimizing raw material waste, lowering machine energy losses associated with unstable operation, and improving overall resource efficiency in textile manufacturing. These findings may also support the development of more systematic maintenance protocols aimed at enhancing productivity, reducing downtime, and promoting long-term manufacturing sustainability [16], [47], [48].

5. CONCLUSION

This study demonstrates that bottom front roller eccentricity in ring spinning significantly degrades PV 30 yarn quality by increasing yarn unevenness (U%) and mass variation (CV%). These findings confirm the critical role of precise roller alignment in maintaining drafting stability and consistent yarn characteristics. Using a paired-sample experimental design, this study isolated bottom front roller eccentricity as a single experimental factor under controlled mechanical and environmental conditions. This approach provided more direct evidence of the influence of roller eccentricity on yarn quality parameters. In contrast, roller eccentricity showed no statistically significant effect on yarn hairiness.

From an industrial engineering perspective, the results highlight the importance of preventive maintenance practices focused on mechanical alignment. Routine monitoring and correction of bottom front roller eccentricity with simple measurement tools, such as dial indicators, can improve yarn uniformity and enhance operational efficiency in ring spinning systems. Preventive alignment maintenance may also contribute to reduced material waste, improved process stability, and more sustainable textile manufacturing operations.

The controlled experimental design strengthened internal validity and enabled more precise causal interpretation of the findings. However, the use of a single machine, single yarn type, and single eccentricity level limits the generalizability of the results to broader industrial conditions.

Future research is recommended to investigate a wider range of roller eccentricity levels across different machine models, fiber compositions, and production environments. Further validation through multi-machine experiments and industrial-scale studies is also recommended to evaluate the applicability of the findings under more diverse manufacturing conditions. Studies with larger sample sizes are also suggested to further examine the potential subtle effects of mechanical misalignment on yarn hairiness.

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DECLARATION OF AI-TOOL USAGE

During the preparation of this manuscript, the authors used Grammarly for English grammar and language editing and DeepL for translation assistance. No AI tools were used for study design, data collection, data analysis, result interpretation, or scientific content generation. All AI-assisted outputs were carefully reviewed and edited by the authors, who take full responsibility for the content of this manuscript.