Sainteks: Jurnal Sain dan Teknik
E-ISSN: 2685-8304
Volume 8, Nomor 02, 2026
http://ejournal.uicm.ac.id/index.php/sainteks/

Cotton Ply Yarn Twist And Filling Stop In Air-Jet Woven Mori Fabric

Andrian Wijayono[1*], Reffli Ghandara[2], Fahmi Fawzy Rusman[3] and Nurfadilah Ikhsani[4]

[1*]Woven Fabric Manufacturing Technology Study Program, Akademi Komunitas Industri Tekstil dan Produk Tekstil Surakarta, Surakarta, Jawa Tengah, 57126
Email: andrianw@kemenperin.go.id
[2]Woven Fabric Manufacturing Technology Study Program, Akademi Komunitas Industri Tekstil dan Produk Tekstil Surakarta, Surakarta, Jawa Tengah, 57126
Email: refflighandara@kemenperin.go.id
[3]Yarn Manufacturing Engineering Study Program, Akademi Komunitas Industri Tekstil dan Produk Tekstil Surakarta, Surakarta, Jawa Tengah, 57126
Email: fahmirusman@kemenperin.go.id
[4]Yarn Manufacturing Engineering Study Program, Akademi Komunitas Industri Tekstil dan Produk Tekstil Surakarta, Surakarta, Jawa Tengah, 57126
Email: nurfadilahikhsani@kemenperin.go.id
*) *Corresponding author*

Abstract: *The aerodynamic interaction between weft yarn and compressed air plays a critical role in determining weaving performance in air-jet looms. Although increasing ply twist is known to reduce yarn hairiness by improving yarn compactness, its influence on actual filling stop behavior under industrial weaving conditions has not been comprehensively investigated. This study investigated how cotton ply yarn twist affects yarn hairiness and filling stop rate during the production of 100% cotton greige (mori) fabric on a Toyoda air-jet loom under commercial manufacturing conditions. Cotton Ne 20 ply yarns were prepared from two Ne 40 single yarns using a two-for-one twisting process with ply twist levels of 400, 600, and 800 TPM while maintaining identical yarn count, fiber composition, and weaving parameters. Yarn hairiness was measured using a COVATEST hairiness tester, whereas weaving performance was evaluated based on the filling stop rate recorded over five weaving repetitions of 100,000 picks for each twist level. One-way ANOVA was performed to assess the effect of ply twist on filling stop rate, followed by Tukey's HSD test for post-hoc comparisons. In addition, linear regression analysis was performed to quantify the observed association between yarn hairiness and filling stop rate. Yarn hairiness decreased progressively from 5.63 $\pm$ 0.06 at 400 TPM to 4.54 $\pm$ 0.05 at 800 TPM, corresponding to an overall reduction of 19.36%. Conversely, the filling stop rate increased from 0.80 $\pm$ 0.84 to 6.20 $\pm$ 1.48 stops per 100,000 picks as the ply twist increased. Statistical analysis confirmed that ply twist significantly affected the filling stop rate ($F = 19.895$, $p < 0.001$). Linear regression showed a strong negative association between yarn hairiness and filling stop rate ($r = -0.855$, $R^2 = 0.731$, $p < 0.001$). However, because both variables varied systematically with ply twist, this association does not establish an independent causal effect of hairiness on filling stop occurrence. The observed increase in filling stop rate with higher ply twist, together with the reduction in yarn hairiness, suggests that changes in yarn surface characteristics may influence weft insertion under compressed airflow. A possible explanation, consistent with previous studies, is that the smoother and more compact yarn surface associated with higher ply twist may reduce aerodynamic interaction during weft insertion. However, this aerodynamic mechanism was not directly measured in the present study. These findings demonstrate an association between ply twist, yarn hairiness, and filling stop behavior under commercial air-jet weaving conditions, providing practical insight into ply yarn design for weaving performance.*
Keywords*: air-jet weaving; cotton ply yarn; filling stop rate; hairiness; ply twist*

DOI: https://doi.org/10.37577/sainteks.v8i02.1163
Received: 07, 2026. Accepted: 09, 2026. Published: 09, 2026

INTRODUCTION

The textile industry continuously seeks improvements in production efficiency, product quality, and manufacturing stability to remain competitive in global markets (Haque et al., 2023; Zhou et al., 2026). In weaving, machine stoppages and yarn breakages reduce loom efficiency and productivity by interrupting machine operation and increasing production losses (Azizah & Wijayono, 2025; Azrul et al., 2025; Çelikkiran & Ünal, 2021; Cioară et al., 2004; Huang et al., 2022). In air-jet weaving, weft stoppages are particularly significant, as effective weft insertion is governed by the interaction among airflow pressure, insertion system, and the yarn characteristics. Air pressure, yarn properties, weft breakage, air velocity, and insertion parameters have been identified as important factors affecting insertion stability and efficiency (Adanur & Turel, 2004; Nazar et al., 2024; Turel et al., 2004). Recent research has further highlighted the role of yarn and process characteristics in achieving stable and consistent weaving performance (Bral et al., 2025; Fahad et al., 2025; Jin et al., 2022; Mebrate et al., 2022; Nazar et al., 2024; Walther et al., 2023).

Air-jet weaving is widely used for high-speed fabric production because compressed airflow rapidly drives the weft through the shedding. The success of this process depends strongly on air–yarn interaction, with yarn manufacturing system, airflow pressure, airflow velocity, yarn ply, yarn twist, yarn hairiness, and yarn count (fineness) influencing weft delivery time and yarn velocity (Adanur & Turel, 2004; Turel et al., 2004). Recent studies further demonstrate that twist level and yarn ply configuration influence the characteristics and performance of cotton ply yarns (Nurazizah et al., 2025; Rusman et al., 2025).

Filling stops represent an important consequence of unsuccessful weft insertion, occurring when the weft fails to complete the required insertion and causes machine stoppage. Previous studies have associated weft stoppages with yarn quality, weft breakage, improper insertion-device adjustment, and inappropriate technological parameters (Cheng & Cai, 2006). Recent research similarly indicates that yarn and machine related conditions contribute to weaving disturbances and defects (Nazar et al., 2024). However, previous research has predominantly examined yarn and machine parameters in relation to insertion velocity, insertion time, twist loss, or fabric properties rather than actual filling stop behavior under industrial weaving conditions (Adanur & Turel, 2004; Admas & Ayele, 2025; Dejene & Ayele, 2024; Ketema & Ayele, 2023).

Yarn hairiness is an important surface characteristic that can modify air–yarn interaction and aerodynamic behavior during insertion. Studies have shown that hairiness affects air drag, while research in air-jet weaving demonstrates that yarn hairiness and structure influence weft yarn velocity and insertion behavior (Admas & Ayele, 2025; Tang et al., 2006). Recent research also identifies hairiness as an important yarn quality characteristic (Fahad et al., 2025). However, its relationship with actual filling stop occurrence remains insufficiently established.

Among yarn structural parameters, ply twist is particularly important for two-ply yarns because it alters fiber arrangement and cohesion and can consequently affect hairiness. Palaniswamy & Mohamed (2006) reported that hairiness decreased with increasing ply twist, while Dhamija et al. (2017) found that ply twist significantly influenced the hairiness of two-ply cotton yarns. Recent studies further confirm the importance of twist and ply configuration in determining cotton ply yarn characteristics and performance (Nurazizah et al., 2025; Rusman et al., 2025). Nevertheless, how these structural modifications translate into actual weaving performance, particularly filling stop behavior in air-jet weaving, remains unclear.

Recent research has examined the effects of weft yarn structure, including twist, hairiness, yarn count, fibre type, and twist loss, on weft behaviour during air-jet weaving (Admas & Ayele, 2025; Dejene & Ayele, 2024; Ketema & Ayele, 2023). Dejene and Ayele (2024), for example, reviewed the effects of yarn structure and fibre type primarily in terms of weft yarn velocity, insertion time, and twist loss, while other studies have investigated twist loss, yarn strength loss, and fabric properties under varying loom and yarn conditions (Admas & Ayele, 2025; Ketema & Ayele, 2023). These studies provide important evidence on how yarn and machine parameters influence weft insertion behaviour, but the response variables largely describe yarn motion, twist stability, or resulting fabric properties rather than the actual occurrence of filling stops during weaving. Therefore, direct experimental evidence linking ply twist and yarn hairiness to actual filling stop rate under controlled commercial air-jet weaving conditions remains limited. The methodological contribution of the present study is to evaluate filling stop rate directly from machine-recorded stoppage events over 100,000 picks per experimental run, while maintaining the yarn count, fibre composition, and key weaving parameters constant. This approach provides production-level evidence of how changes in ply yarn structure are reflected in actual weaving stoppage behaviour, complementing previous studies based primarily on yarn velocity, twist loss, insertion time, or fabric properties.

Therefore, the effect of cotton ply yarn twist level on yarn hairiness and filling stop rate during the production of 100% cotton greige (mori) fabric using a Toyoda air-jet loom under actual industrial conditions will be investigated. Cotton ply yarns with 400, 600, and 800 TPM were prepared using a two-for-one twisting process while maintaining identical yarn count, fiber composition, and weaving parameters. Yarn hairiness was evaluated using a COVATEST hairiness tester, while weaving performance was assessed through filling stop measurements during industrial production trials. The novelty of this study lies in experimentally linking ply twist and yarn hairiness with actual filling stop behavior under commercial air-jet weaving conditions. The findings are expected to clarify the relationship between yarn structural characteristics and air–yarn interaction and provide practical guidance for optimizing ply yarn design to improve weaving efficiency.

METHOD

A quantitative experimental approach was adopted in this study to examine how cotton ply yarn twist affects the filling stop rate (FSR) during the production of 100% cotton greige (mori) fabric on an air-jet loom. The experiments were conducted under actual industrial production conditions to ensure that the results accurately represented weaving performance in commercial manufacturing. Figure 1 shows the performed experiment in the production department of a commercial weaving mill equipped with Toyoda air-jet looms operating under continuous industrial manufacturing conditions.

Figure 1. Toyoda Air-Jet Loom Used For The Experimental Weaving Trials Under Industrial Production Conditions

The experimental fabric was woven in a plain weave (1/1) structure with a balanced construction of 60 ends/inch × 60 picks/inch. The warp yarn consisted of carded cotton Ne 20, whereas the weft yarn was produced by plying two carded cotton Ne 40 single yarns to obtain a Ne 20 cotton ply yarn. The ply yarns were manufactured using a two-for-one twisting machine by adjusting the spindle speed to obtain three ply twist levels of 400, 600, and 800 TPM. The target ply twist levels were verified during yarn preparation using the twist testing procedure before the weaving trials were conducted. Because the original single yarns possessed a Z-twist, all ply yarns were produced with an S-twist direction to achieve a balanced ply yarn structure. Three ply twist levels, namely 400, 600, and 800 TPM, were prepared while maintaining the same resultant yarn count (Ne 20) and identical fiber composition. This experimental approach minimized the potential influence of yarn fineness or linear density, allowing the association of ply-yarn twist level with weft insertion performance to be evaluated under controlled yarn specifications.

The weaving trials were conducted on a Toyoda air-jet loom operating at a constant speed of 600 rpm with a reed width of 127 cm. To minimize the influence of other process variables, all weaving parameters were maintained constant throughout the experiments, including the warp yarn specification, fabric construction, loom speed, reed count (60 dents per 2 inches), reed width, air pressure, nozzle timing, and other machine operating conditions. The same warp beam and identical machine settings were used for all experimental trials to minimize process variation. The main nozzle (MN) was activated at 92°, whereas the sub nozzles (SN1–SN5) were sequentially activated at 94°, 98°, 102°, 106°, and 110°, respectively. Both the main nozzle and sub nozzles were operated at a constant air pressure of 6 bar throughout the experiments. The principal loom timing was maintained at 75° (shedding), 120° (picking), 150° (beating-up), 180° (front dead center), and 210° (let-off).

The ply twist level (400, 600, and 800 TPM) was defined as the experimental factor. For each ply-twist level, five yarn packages were assigned to five corresponding weaving runs. Each package was identified as P1–P5 and assigned to weaving run W1–W5, respectively, resulting in the package–run correspondence P1–W1, P2–W2, P3–W3, P4–W4, and P5–W5. Before weaving, each assigned yarn package was characterized for hairiness, and the same package was subsequently used as the weft-yarn source for its corresponding weaving run. Each weaving run comprised 100,000 weft insertions under identical operating conditions.

Five repeated runs were conducted for each ply-twist level to provide replicated observations of filling stop behaviour over a standardized observation window of 100,000 weft insertions per run. This resulted in 500,000 weft insertion events being observed for each ply-twist level. The same loom, warp beam, warp yarn specification, and controlled machine settings were maintained throughout the experiments to minimize process variability. The five runs were treated as repeated observational runs under the same controlled production setup rather than as fully independent machine-level experiments. Each 100,000-pick run was treated as one observational unit for calculating and comparing the filling stop rate. Filling stop events were automatically recorded through the loom monitoring system, as presented in Figure 2.

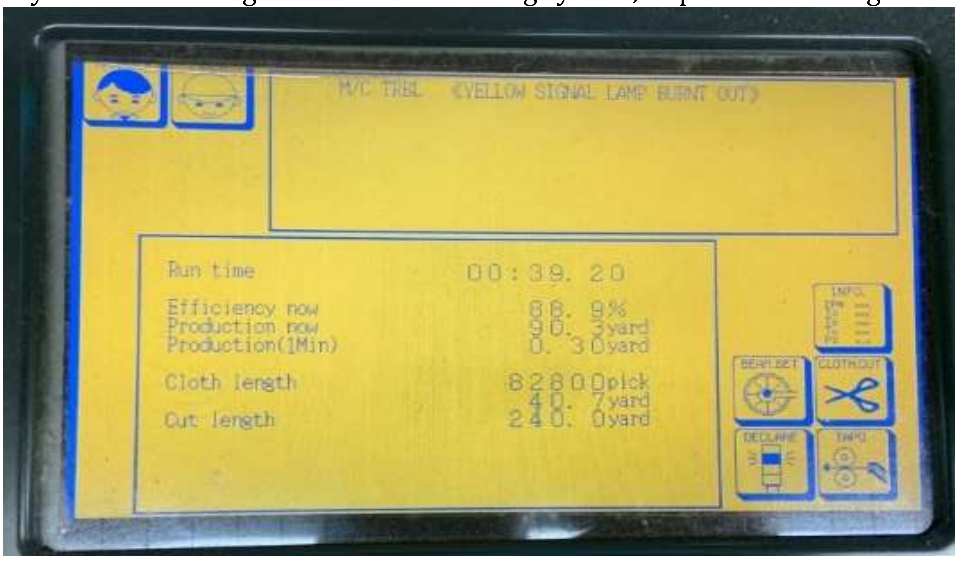

Figure 2. Loom Monitoring Interface Of The Toyoda Air-Jet Loom Used For Recording Filling Stop Events And Production Parameters During The Weaving Trials

The filling stop frequency was normalized to the number of inserted picks to provide a standardized basis for comparison among the experimental runs. This normalization enables a fair comparison among different experimental conditions regardless of production duration. The filling stop rate (FSR) was calculated using Equation (1).

$$FSR = \frac{N_{fs}}{N_p} \times 100{,}000 \quad (1)$$

where FSR is the filling stop rate (stops per 100,000 picks), N_{fs} is the total number of filling stops recorded during weaving, and N_p is the total number of inserted picks. This normalization enables a fair comparison among different experimental conditions regardless of production duration.

To investigate the potential relationship between yarn surface characteristics and filling stop behaviour, the hairiness of the plied yarn was determined using a COVATEST hairiness tester (Textechno, Germany) equipped with an optical hairiness measurement module. Hairiness testing was conducted in the Quality Control Laboratory under standard conditions (27 ± 1°C and 65 ± 2% RH) at a testing speed of 400 m/min. Before the weaving trials, the five yarn packages assigned to each ply-twist level were characterized for hairiness. Each yarn package was measured three times under identical testing conditions. The three measurements obtained from each package were treated as repeated measurements and averaged to obtain one package-level mean hairiness value. Thus, each package contributed one statistical observation for hairiness, resulting in five package-level observations (n = 5) for each ply-twist level. Although 15 individual hairiness measurements were obtained at each twist level, these measurements represented three repeated measurements from each of five yarn packages and were therefore not treated as 15 independent observations. The resulting package-level mean hairiness values were then paired with the filling stop rates recorded from their corresponding weaving runs (P1–W1, P2–W2, P3–W3, P4–W4, and P5–W5). This pairing provided five package–weaving-run observations for each ply-twist level and 15 paired observations across the three ply-twist levels for analysis of the hairiness–FSR association.

The experimental results were subjected to one-way analysis of variance (ANOVA) to assess differences in filling stop rate among the three ply-twist levels. For this analysis, each 100,000-pick weaving run was treated as one observational unit, resulting in five FSR observations per ply-twist level (n = 5). The normality and homogeneity of variance assumptions were examined using the Shapiro–Wilk and Levene's tests, respectively. A significance level of $p < 0.05$ was used to determine statistical significance. Where significant differences were detected by ANOVA, Tukey's Honest Significant Difference (HSD) post-hoc test was subsequently conducted to identify differences between ply-twist levels. To examine the association between yarn hairiness and filling stop rate, linear regression analysis was performed using the 15 package-level mean hairiness values paired with the corresponding FSR values from the 15 weaving runs. Each pair represented one yarn package and its associated weaving run (P1–W1 through P5–W5 at each of the three ply-twist levels). The regression coefficient, coefficient of determination (R^2), and significance level were evaluated at $p < 0.05$. Because ply twist was systematically varied and was expected to influence both hairiness and FSR, the regression was interpreted as an overall association across the investigated ply-twist levels rather than as evidence of an independent causal effect of hairiness on FSR. All statistical analyses were carried out using SPSS Statistics version 25 (IBM Corp., Armonk, NY, USA).

The complete experimental workflow, beginning with weft yarn preparation through two-for-one twisting, followed by hairiness characterization, air-jet weaving under constant operating conditions, filling stop measurement, and statistical analysis, is summarized in Figure 3. Table 1 shows the specification employed throughout the experiments.

Table 1. Controlled Weaving Parameters And Experimental Conditions

Category	Parameter	Specification
Fabric	Fabric type	100% cotton greige (mori-fabric)
	Weave structure	Plain weave (1/1)
	Construction	60 ends/in × 60 picks/in
Warp Yarn	Yarn Count	Carded Cotton Ne_1 20
	Twist constant (α_{Ne})	3,98
	Twist	700 TPM (Z-Twist Direction)
Weft Yarn	Single yarn count	Carded Cotton Ne_1 40
	Twist constant (α_{Ne})	3,41
	Single yarn twist direction	800 TPM (Z-Twist Direction)
	Number of ply	2-ply yarn
	Ply yarn count	Ne_1 20 (2 × Ne_1 40)
	Ply yarn twist direction	S-Twist Direction
	Variable parameter	Ply twist (400, 600, 800 TPM)
	Ply yarn manufacturing	Two-for-one twisting machine
Loom settings	Loom type	Toyoda Air-Jet Loom
	Loom speed	600 rpm
	Reed width	127 cm
	Reed count	60 dents/2 in
	Main nozzle pressure	6 bar
	Sub nozzle pressure	6 bar
	Main nozzle timing	92°
	Sub nozzle timing	SN1=94°, SN2=98°, SN3=102°, SN4=106°, SN5=110°
	Shedding timing	75°
	Picking timing	120°
	Beating-up timing	150°
	Front dead center	180°
	Let-off timing	210°
Experiment	Weaving runs per ply-twist level	5
	Observation length per run	100,000 inserted picks
	FSR observations per ply-twist level	5
Hairiness test	Hairiness tester device	COVATEST (Textechno, Germany)
	Yarn packages per ply-twist level	5
	Measurements per package	3 repeated measurements
	Statistical unit	Package-level mean
	Test condition	RH 65 ± 2%; 27 ± 1°C; 400 m/min

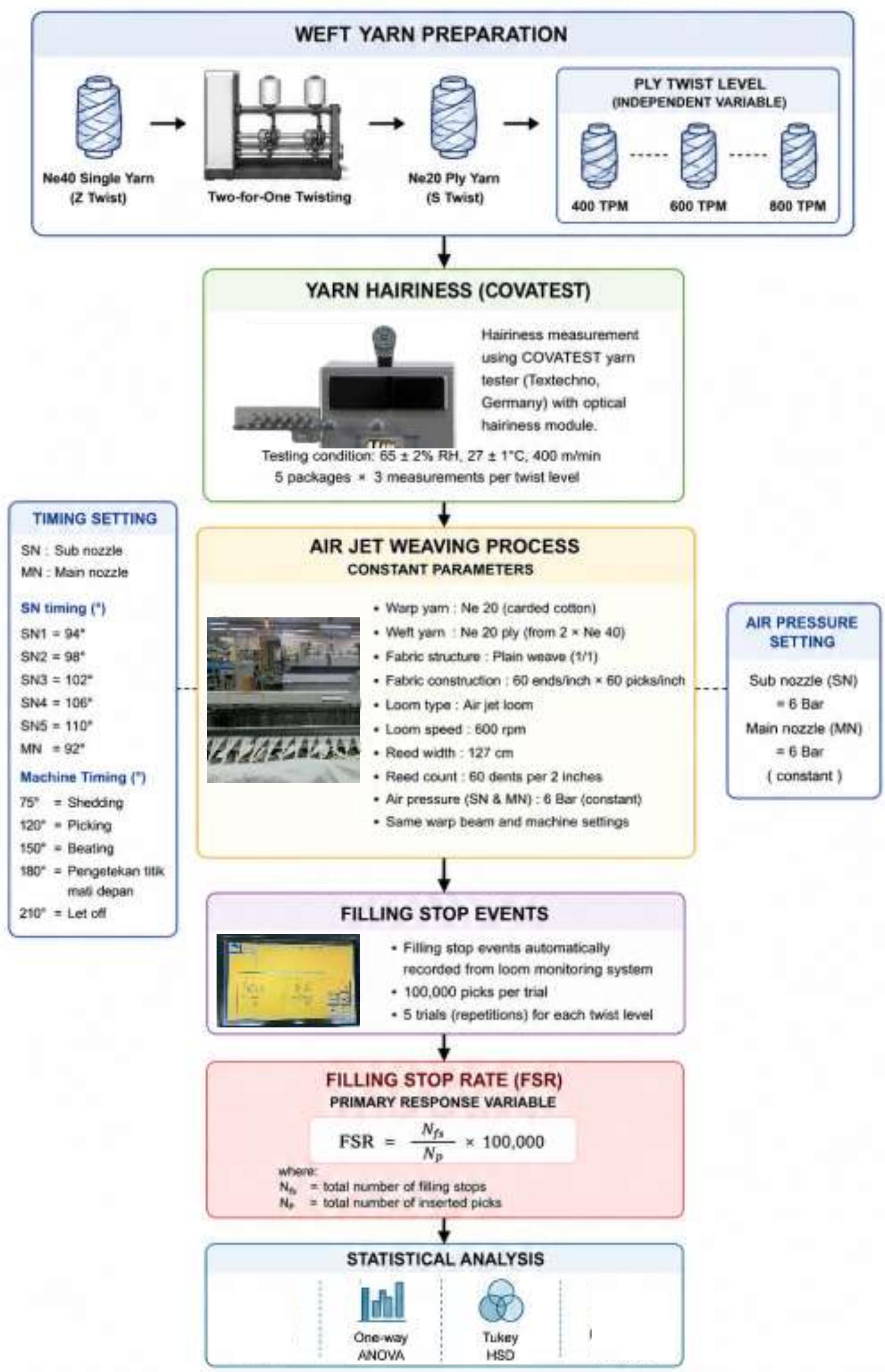

Figure 3. Experimental Workflow For Evaluating The Influence Of Plied-Yarn Twist Level (Cotton Yarn) On Filling Stop Rate During Air-Jet Weaving

RESULT AND DISCUSSION

The influence of cotton ply-yarn twist level on filling stop rate (FSR) and yarn hairiness was investigated under actual industrial weaving conditions using a Toyoda air-jet loom. The experimental results showed that increasing the ply-twist level was accompanied by a decrease in yarn hairiness and an increase in filling stop rate under the investigated air-jet weaving conditions.

Hairiness characteristics of cotton ply yarn

The measured yarn hairiness values obtained from the COVATEST hairiness tester are presented in Table 2, whereas the relationship between ply twist and yarn hairiness is illustrated in Figure 4. The boxplot demonstrates a progressive downward shift in the distribution of hairiness values as the ply twist increased from 400 to 800 TPM. The three repeated measurements within each yarn package were closely clustered, while the package-level means showed a consistent decrease in hairiness with increasing ply twist. In addition, the relatively narrow spread of the data indicates good measurement repeatability among the five yarn packages and three repeated measurements performed for each package. A consistent decrease in hairiness was observed with increasing ply twist. The average hairiness decreased from 5.63 ± 0.06 for the yarn twisted at 400 TPM (ply-to-single twist ratio = 1/2) to 5.12 ± 0.06 at 600 TPM (ratio = 3/4), and reached the lowest value of 4.54 ± 0.05 at 800 TPM (ratio = 1).

The percentage reduction in yarn hairiness is summarized in Table 3. Increasing the ply twist from 400 to 600 TPM reduced the average hairiness by 9.06%, whereas a further increase from 600 to 800 TPM produced an additional 11.33% reduction. Overall, the hairiness index decreased by approximately 19.36% between the lowest and highest ply twist levels. This continuous reduction indicates that increasing the ply twist progressively improved yarn compactness and effectively restrained protruding surface fibers. Furthermore, the clear separation between the distributions shown in Figure 4 supports the observed decreasing trend in hairiness with increasing ply twist.

Table 2. Hairiness Values Of Plied-Cotton-Yarn On Different Ply Twist

Twist level of single yarn (TPM)	Twist level of plied yarn (TPM)	Twist ratio of single-yarn and ply-yarn	Yarn package	Hairiness index Measurement			Mean ± SD
				1	2	3	
800	400	1/2	P1	5,61	5,58	5,55	5,58 ±0,03
			P2	5,72	5,69	5,66	5,69 ±0,03
			P3	5,54	5,57	5,52	5,54 ±0,03
			P4	5,63	5,6	5,65	5,63 ±0,03
			P5	5,67	5,71	5,69	5,69 ±0,02
						Overall	5,63 ±0,06
	600	3/4	P1	5,18	5,2	5,16	5,18 ±0,02
			P2	5,09	5,12	5,08	5,10 ±0,02
			P3	5,15	5,17	5,13	5,15 ±0,02
			P4	5,03	5,01	5,06	5,03 ±0,03
			P5	5,12	5,15	5,1	5,12 ±0,03
						Overall	5,12 ±0,06
	800	1	P1	4,58	4,55	4,56	4,56 ±0,02
			P2	4,49	4,51	4,53	4,51 ±0,02
			P3	4,61	4,59	4,62	4,61 ±0,02
			P4	4,45	4,47	4,48	4,47 ±0,02
			P5	4,54	4,56	4,52	4,54 ±0,02
						Overall	4,54 ±0,05

Table 3. Hairiness Reduction (%) Of Plied-Cotton-Yarn On Different Ply Twist

Twist level of plied yarn (TPM)	Twist ratio of single-yarn and ply-yarn	Average hairiness index	Reduction (%)
400	1/2	5,63	-
600	3/4	5,12	9,06%
800	1	4,54	11,33%

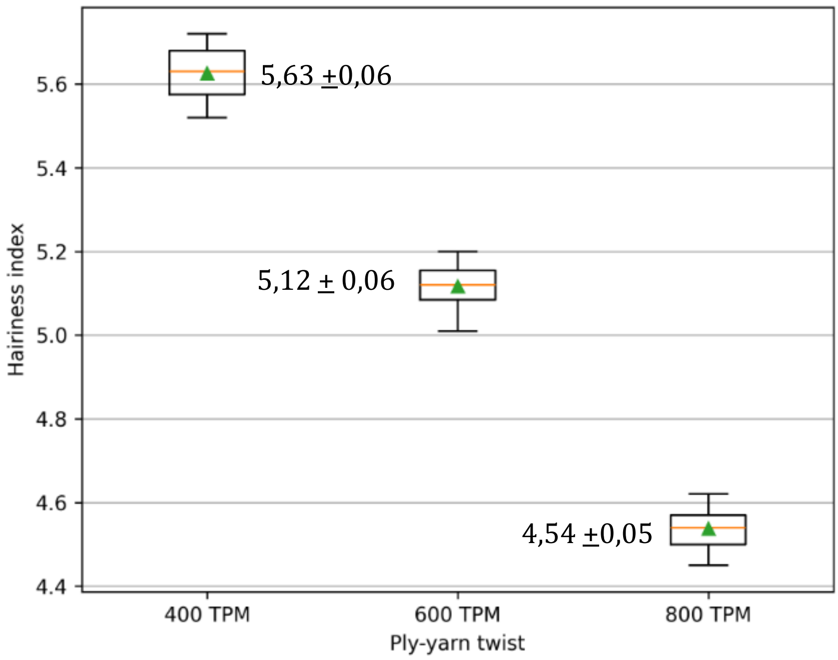

Figure 4. Distribution Of Hairiness Index At Different Ply Twists

This behavior can be explained by the structural modification occurring during the two-for-one twisting process. Increasing the ply twist causes the two constituent single yarns to wrap around each other more tightly, resulting in greater radial compression and enhanced fiber migration toward the yarn core. Consequently, a larger proportion of protruding fibers became integrated into the yarn body, while the increased binding effect between the constituent single yarns enhanced yarn compactness. This structural modification reduced the number of free fiber ends extending from the yarn surface, thereby producing a smoother and more compact ply yarn with a lower hairiness index.

Palaniswamy & Mohamed (2006) demonstrated that increasing ply twist effectively reduces yarn hairiness by mechanically trapping protruding fibers between the constituent yarns. Their study showed that the enhanced binding generated by higher ply twist improved yarn compactness and suppressed exposed surface fibers, which closely agrees with the continuous decrease in hairiness observed in the present work.

Since all yarns possessed the same resultant yarn count (Ne 20), identical fiber composition, identical single-yarn twist (800 TPM, Z-twist), and the same ply-twist direction (S-twist), the observed reduction in hairiness was evaluated primarily in relation to the increase in ply-twist level under controlled yarn specifications. Maintaining these variables constant helped minimize the potential influence of yarn fineness, fiber properties, and raw-material characteristics on the observed hairiness values.

The reduction in hairiness observed in this study agrees with the fundamental theory of ply yarn structure, in which increasing twist enhances yarn compactness by increasing inter-fiber cohesion and reducing the number of free fiber ends on the yarn surface. Similar observations have been reported for cotton ply yarns, where increasing the ply-to-single twist ratio consistently improved fiber binding and reduced yarn hairiness (Palaniswamy and Mohamed, 2006). Collectively, these findings indicate that ply twist is one of the principal structural parameters governing yarn surface characteristics and compactness.

From a weaving perspective, the reduction in yarn hairiness is expected to modify the influence of pressured airflow and yarn surface properties during weft insertion. Since yarn transport in an air-jet pick insertion depends on the aerodynamic interaction, changes in yarn surface characteristics may influence the insertion behavior. However, the effect of reduced hairiness on weaving performance cannot be inferred solely from yarn morphology and therefore requires direct evaluation through filling stop measurements, as discussed in the following section.

It is noteworthy that the lowest hairiness was obtained when the ply twist reached a twist ratio of 1.0 relative to the single-yarn twist (800 TPM). This finding suggests that equalizing the plied-yarn twist level to the single-yarn twist level produced higher compact structure among the investigated conditions. Within the investigated twist range, increasing the ply twist continuously reduced the yarn hairiness without any indication of reversal in the observed trend.

Effect of ply twist on filling stop rate

The weaving performance obtained under identical air-jet weaving conditions is summarized in Table 4, whereas the corresponding filling stop rates are presented in Figure 5. In contrast to the decreasing trend observed for yarn hairiness, the filling stop rate exhibited an increasing trend as the ply twist increased from 400 to 800 TPM. The average filling stop rate increased from 0.80 ± 0.84 stops per 100,000 picks at 400 TPM to 4.40 ± 1.67 stops per 100,000 picks at 600 TPM and further increased to 6.20 ± 1.48 stops per 100,000 picks at 800 TPM. These results indicate that increasing the ply twist did not improve weaving performance under the investigated operating conditions. Instead, the yarn with the lowest ply twist (400 TPM), which also exhibited the highest hairiness, showed the lowest filling stop rate.

Table 4. Filling Stop Rate At Different Ply Twist Levels

Single-yarn twist (TPM)	Ply-yarn twist (TPM)	Twist ratio	Weaving repetition	Filling stop rate (stops/100,000 picks)
800	400	1/2	W1	0
			W2	1
			W3	2
			W4	1
			W5	0
			Overall	0,80 ± 0,84
	600	3/4	W1	4
			W2	3
			W3	5
			W4	7
			W5	3
			Overall	4,40 ± 1,67
	800	1	W1	6
			W2	4
			W3	8
			W4	6
			W5	7
			Overall	6,20 ± 1,48

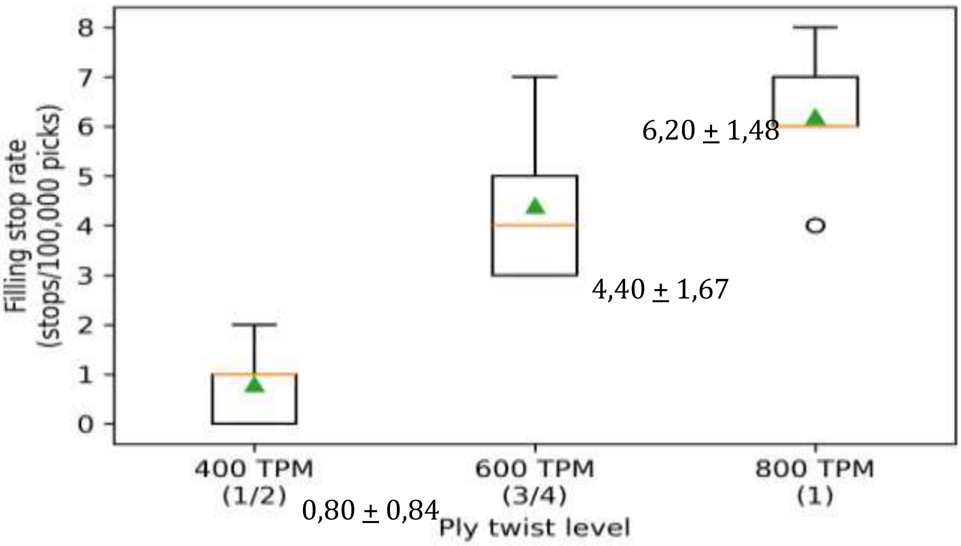

Figure 5. Distribution Of Filling Stop Rate At Different Ply Twist Levels

The boxplot presented in Figure 5 shows an upward shift in the distribution of filling stop rates with increasing ply twist. The relatively narrow spread of the data within each experimental group indicates good repeatability among the five weaving repetitions performed for each twist level.

Unlike the previous section, which demonstrated that increasing ply twist significantly reduced yarn hairiness, the present results indicate that lower hairiness did not necessarily improve weaving performance under air-jet weaving conditions. This finding suggests that the relationship between yarn surface characteristics and weaving performance is more complex than a simple reduction in protruding fibers.

The weft is delivered by the high-pressure compressed airflow discharged from the nozzle (main nozzle) and subsequently accelerated by the sub-nozzles series. Consequently, the weft insertion efficiency depends on the influence of the yarn surface and the pressured airflow. According to Adanur & Turel (2004), the pressured airflow giving a driving force on the weft using frictional interaction (the yarn surface and compressed airflow interaction). Their study demonstrated that highly twisted yarns generally exhibit lower insertion velocity because their smoother surfaces generate lower aerodynamic drag. Similar observations were reported by Admas & Ayele (2025), who found that yarns with higher hairiness achieved higher insertion velocity than smoother yarns, indicating that protruding fibers enhance the frictional interaction between the yarn and the airflow.

Increasing the ply twist reduced the hairiness index by approximately 19.36%, indicating a smoother and more compact yarn surface. According to Adanur and Turel, yarn hairiness can increase friction between the yarn surface and the surrounding airflow, which may facilitate yarn transport during air-jet insertion. Based on this previous understanding, one possible explanation for the present findings is that the lower hairiness associated with higher ply twist may reduce air–yarn interaction during insertion. Under the constant air pressure used in the present experiments, this change in yarn surface characteristics may have reduced the aerodynamic driving effect acting on the weft yarn and consequently contributed to less efficient weft insertion. However, this aerodynamic mechanism was not directly verified in the present study because aerodynamic drag, yarn velocity, and air–yarn interaction were not measured. Therefore, the aerodynamic interpretation should be regarded as a proposed mechanism based on previous literature rather than a directly demonstrated causal mechanism.

This interpretation is consistent with the analysis of Dejene and Ayele (2024), who identified longitudinal aerodynamic drag as an important driving force for yarn acceleration during air-jet insertion and reported that increasing yarn twist can reduce the aerodynamic drag associated with yarn–air interaction. The literature therefore provides a plausible basis for interpreting the present trend; however, the present experiments directly demonstrated only the reduction in hairiness and the increase in filling stop rate with increasing ply twist. The observed increase in filling stop rate from 400 to 800 TPM is therefore interpreted as being associated with changes in yarn surface characteristics, while the specific aerodynamic pathway remains a hypothesis requiring direct measurements of yarn velocity, aerodynamic drag, or air–yarn interaction in future work.

To further quantify the observed relationship between yarn hairiness and filling stop rate, a linear regression analysis was performed using the package-level mean hairiness values and the corresponding filling stop rates from the five weaving repetitions at each ply twist level. Each yarn package was matched with its corresponding weaving repetition (P1–W1, P2–W2, P3–W3, P4–W4, and P5–W5), resulting in 15 paired observations across the three ply twist levels. The regression analysis showed a strong negative association between yarn hairiness and filling stop rate ($r = -0.855$, $R^2 = 0.731$, $p < 0.001$). Thus, lower hairiness values were associated with higher filling stop rates under the investigated experimental conditions. However, this statistical association should be interpreted with caution because both yarn hairiness and filling stop rate varied systematically with ply twist. Therefore, the regression result demonstrates an association between the two variables but does not establish an independent causal effect of yarn hairiness on filling stop occurrence.

Because loom speed, air pressure, nozzle timing, reed specification, warp yarn, and other machine settings were maintained constant throughout the experiments, the observed differences in filling stop rate were evaluated in relation to the different ply-twist levels under otherwise controlled weaving conditions. Admas and Ayele (2025) reported that higher yarn hairiness can increase weft yarn insertion velocity during air-jet weaving, suggesting that yarn surface characteristics may affect air–yarn interaction. In the present study, the yarn with the highest hairiness at 400 TPM exhibited the lowest filling stop rate, whereas the yarn with the lowest hairiness at 800 TPM exhibited the highest filling stop rate. The regression analysis further demonstrated a strong negative association between hairiness and filling stop rate. Nevertheless, because both variables changed systematically with ply twist, the observed association cannot be interpreted as evidence that hairiness independently determines filling stop occurrence. The result therefore provides quantitative support for an association between yarn surface characteristics and filling stop behavior, while the underlying aerodynamic mechanism remains a proposed explanation rather than a directly demonstrated causal relationship.

The observed association between yarn hairiness and filling stop rate should not be interpreted solely in terms of yarn smoothness or compactness. Although higher ply twist reduced hairiness, the corresponding increase in filling stop rate suggests that a smoother yarn surface does not necessarily provide better weft insertion performance under air-jet weaving conditions. The present results therefore indicate that yarn surface characteristics should be considered together with the aerodynamic requirements of the weft insertion process rather than evaluated solely from the perspective of yarn compactness.

The results demonstrate that minimizing yarn hairiness does not automatically guarantee improved air-jet weaving performance. Although lower hairiness is generally desirable for improving yarn appearance and compactness, air-jet weaving relies on sufficient aerodynamic influence of the pressured airflow and the degree of hairiness. Therefore, the optimum ply twist should be selected by balancing yarn compactness with adequate air–yarn interaction to achieve stable weft insertion while minimizing filling stop occurrences. This also indicates that optimizing ply twist should not focus solely on minimizing yarn hairiness. Similar to the observations reported by Wanti & Setiawati (2024), yarn surface characteristics represent an important quality parameter affecting downstream textile processing. However, the present findings suggest that, under the investigated air-jet weaving conditions, an excessively smooth yarn surface may be associated with reduced aerodynamic interaction with the compressed air stream, which could contribute to a higher filling stop rate. This interpretation remains a proposed mechanism because the relevant aerodynamic parameters were not directly measured in the present study.

Statistical evaluation

Prior to the one-way ANOVA, the assumptions of normality and homogeneity of variance were assessed. The Shapiro–Wilk test did not indicate a significant departure from normality for the FSR data at 400 TPM (W = 0.881, p = 0.314), 600 TPM (W = 0.881, p = 0.314), or 800 TPM (W = 0.956, p = 0.777). Levene's test also indicated that the homogeneity of variance assumption was not violated (F(2, 12) = 0.877, p = 0.441). These results supported the use of one-way ANOVA to compare FSR among the three ply-twist levels.

The filling stop rates obtained at 400, 600, and 800 TPM were compared using a one-way analysis of variance (ANOVA). Table 5 shows the outcome of the statistical test.

Table 5. One-way ANOVA and Tukey's HSD Results For Filling Stop Rate

(a) One-way ANOVA

Variation	SS	df	MS	F	p-value
Between groups	75.600	2	37.800	19.895	<0.001
Within groups	22.800	12	1.900		
Total	98.400	14			

(b) Tukey's HSD

Ply twist	ΔMean	95% CI	p-value	Result
400 - 600 TPM	-3.600	-5.926 to -1.274	0.004	Significant
400 - 800 TPM	-5.400	-7.726 to -3.074	<0.001	Significant
600 - 800 TPM	-1.800	-4.126 to 0.526	0.139	Not significant

A significant variation in filling stop rate was observed among the three ply twist levels, as confirmed by the ANOVA results (F = 19.895, p < 0.001). Thus, the differences in filling stop rate were considered statistically meaningful and unlikely to arise solely from random variation within the experiment. Pairwise comparisons were subsequently conducted using Tukey's HSD procedure to further examine the differences among the three ply twist conditions. A significant difference was found between 400 and 600 TPM (p = 0.004), as well as between 400 and 800 TPM (p < 0.001). In contrast, the difference between the 600 and 800 TPM treatments was not significant (p = 0.139), even though the latter exhibited a slightly greater mean filling stop rate.

These statistical findings are consistent with the experimental observations presented in Figure 5. Increasing the ply twist from 400 TPM to 600 TPM significantly increased the filling stop rate (p = 0.004), whereas a further increase from 600 TPM to 800 TPM produced only a numerical increase that was not statistically significant (p = 0.139).

Overall, the statistical analysis indicates that filling stop rate differed significantly among the three ply-twist levels. The results further indicate that the statistically significant differences occurred between 400 TPM and both 600 and 800 TPM, whereas the increase from 600 to 800 TPM was numerical but not statistically significant. The statistical results confirm that ply twist significantly affected filling stop rate, while the observed relationship with hairiness provides a basis for discussing a possible aerodynamic mechanism.

CONCLUSIONS

Under actual industrial air-jet weaving conditions, cotton ply yarn was evaluated in terms of its hairiness and filling stop behavior. The results showed that increasing the ply twist level from 400 to 800 TPM was accompanied by a reduction in yarn hairiness, which is consistent with the expected increase in yarn compactness associated with higher ply twist. In contrast, the filling stop rate increased numerically from 0.80 ± 0.84 stops per 100,000 picks at 400 TPM to 6.20 ± 1.48 stops per 100,000 picks at 800 TPM. The statistical analysis indicated that filling stop rate differed significantly among the three ply-twist levels, with significant differences between 400 and 600 TPM and between 400 and 800 TPM, whereas the difference between 600 and 800 TPM was not statistically significant. The regression analysis showed a strong negative association between yarn hairiness and filling stop rate ($r = -0.855$, $R^2 = 0.731$, $p < 0.001$). However, because both variables varied systematically with ply twist, this association does not establish an independent causal effect of hairiness on filling stop occurrence. The observed trend is therefore interpreted as an association between yarn surface characteristics and filling stop behavior under the investigated weaving conditions. A possible aerodynamic explanation is that the smoother and more compact yarn surface associated with higher ply twist may alter the interaction between the yarn and compressed airflow during weft insertion. However, this mechanism was not directly measured in the present study. From an industrial perspective, the findings indicate that optimization of ply twist should not focus solely on minimizing yarn hairiness. Instead, yarn compactness should be considered together with the aerodynamic requirements of air-jet weft insertion to achieve stable weaving performance. Future research should directly quantify yarn insertion velocity, aerodynamic drag, and air–yarn interaction to verify the proposed mechanism. Further investigations involving different yarn counts, fibre types, ply constructions, and air-jet weaving parameters are also recommended to establish more comprehensive guidelines for optimizing ply twist under industrial weaving conditions.

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