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Wicking behavior of plied siro-spun yarns

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The wicking behaviour of yarns is a fundamental attribute of fabric comfort. The effect of varying the number of plies of Siro spun ring cotton yarns and of yarn variables such as Twist factor (TF), diameter, twist angle, and linear density, on the optimization of wickability was considered. Siro spun yarns of 32.8 tex (3.09 & 3.67 TF) and 24.5 tex (3.49 TF) in single, double, triple, four, and five-ply configurations forming the platform of this study. The twist level was maintained at 540, 641, and 705 twists per meter (TPM) for 32.8, 32.8, and 24.5 tex Siro yarns. The wicking rate followed a similar trend in Siro-plied yarns; however, when converted to ply yarns, a decreasing trend of wicking height and wicking rate was observed. The wicking height was achieved at the highest at a Twist factor of 3.09. The two-plied Siro spun yarn showed optimal capillaries with twist angle, α (29 to 32) and packing coefficient, μ (0.20 to 0.24) which produced a maximum wicking height of 15.03 cm at a value of 2.78 TF. The higher-plied Siro yarns exhibited larger diameter capillaries, which exerted a lesser wicking force than smaller diameter capillaries. This study will provide a fundamental background for the development of high-quality fabric. The Siro ring-spun bipartite yarns will explore new roles in product development.

Keywords: Plied yarns, Siro spun ring yarn, Twist factor , Wicking height, Yarn linear density,Yarn diameter (volume),Twist angle, Packing coefficient, Vertical wicking, Yarn extension & tenacity

1 Introduction

Wicking is the spontaneous flow of a liquid in a porous substrate, driven primarily by capillary forces[1]. The wicking potential of fibrous structures is highly ranked due to its decisive role in fabric engineering and comfort[2]. The yarn twist and twist insertion tension are two crucial parameters to decide the yarn wickability. The other factors, such as constituent fibre orientation, pore size distribution and heterogeneous pore shape, are also important factors in liquid rise in the yarns [3]. The twist level and number of plies significantly influenced the wicking height in cotton yarns [4]. The role of fibre is also crucial in yarn wicking; coarse wool fibres offer better wickability than fine fibres in woollen yarns. The wicking rate was highest in ring yarns and lowest in compact yarns, with intermediate wicking rates observed for compact Siro and Siro yarns [5]. The effect of yarn ply was investigated in various coarse count yarns[6]. In the case of plied cotton yarns, the difference in wicking height between 2-ply yarn and other higher-plied yarns was more pronounced in finer yarns. The vertical wicking behaviour was studied as a function of twist and ply number[7]. The wicking height of ring yarns was proved to be a function of twist factor,fibre type, yarn structure, fibre packing coefficient, and migration[8,9].The wicking height was decreased by increasing yarn tightness or compactness in ring and siro-ring-spun polyester yarns[10]. The wicking height was also increased with decreasing twist coefficient and yarn compactness in plied Siro compact yarns[10]. The interlacement pattern of yarns in woven fabrics is called the weave, and it affects the wickability of woven fabrics. The twill-weave fabrics exhibited a better correlation between wicking height and yarn fineness[11]. The Washburn capillary theory-based dual-scale model was verified by the capillary-rise test of KFP assemblies at various packing densities ranging from 0.08 g/cm3 to 0.14 g/cm3[12]. The experimental results show good consistency with theoretical values at low packing densities, but the deviation increases with increasing packing density.The Post-hoc test method was used to analyse the wicking behaviour of ring-spun yarns and found that fibre type, doubling and twist level were crucial factors[13]. During the study of fabric geometry and moisture management, the porosity in the top

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layer was found to be crucial[14]. The use of a polyester fabric composite for moisture transfer, combined with cotton or wool for absorption, enhances comfort by effectively wicking sweat away from the body. An embossed jersey structure for fast liquid transport in the sports wear fabrics was studied. The jersey structure allows higher liquid transport without spreading, helping to prevent liquid diffusion and condensation[15]. The fibre packing coefficient in yarn structures played a decisive role in deciding the wicking height. The average capillary size was higher in ring yarns than in compact yarns, which generates higher capillary pressure in compact yarns[16]. The smaller capillaries create sufficient drag to slow the rise in liquid height[17]. The optimal capillary size was proven to cause the fastest water entry into yarn pores. The larger pores offered lower capillary pressure, slowing the rise of water through yarns[18]. The open-end yarns offered the highest wicking height with a twist factor of 4.18. High-twist yarns showed a low water transport rate, and low-twisted yarns also showed a low water transport rate due to a substantial reduction in the number and continuity of the interferer capillaries[19]. The wicking rate was decreased in polyester spun yarns by increasing the twist factor with varying twists from (22 to 49) turns per cm due to a reduction in capillary size[20].

The above present research gaphighlight the need to investigate the wicking behaviour of different plied Siro spun yarns produced at different twist levels and yarn linear density. The effects of yarn diameter, helix angle, and packing coefficient on Siro-plied yarn with different numbers of plies and various twist levels were investigated to provide a fundamental research output that serves as a base for numerous product developments. Therefore, the prime objectives of this research work are to measure the vertical wicking height of ring-spun, plied Siro yarns produced from the same fibre type and three different twist levels. The next objective is to compare the wicking heights of plied Siro spun yarns at different yarn linear density and twist factor levels. This work aims to calculate the yarn diameter (volume), helix angle, and packing coefficient for each plied siro-spun yarn, and compare the measured and calculated results. The next aim is to estimate the effect of yarn's tenacity and extension on the wicking behaviour of plied siro spun yarns.Various statistical parameters, such as F-value, P-value and R^2, are used in ANOVA test results.

The Siro plied yarns, which are widely used in sportswear, especially for T-shirt manufacturing, were not selected for study of wicking behaviour in previous studies. The Siro plied yarns of different linear densities and twist factors are selected to fill this research gap and provide a scientific platform for product development.

2 Materials and Methods

2.1 FibreDetails

The average staple length of fibre was 28.4 mm, which is characteristic of a staple cotton variety fibre. The micronaire value of cotton fibre was found to be 3.8. The breaking tensile strength and elongation of cotton fibre were found, i.e., 28.5 g/tex and 5.6% respectively, at 1/8” fixed gauge length. The ASTM D 1445/D1445M-12 test method was used to assess the breaking strength and elongation of cotton fibres using a flat bundle of cotton fibres[21]. The ASTM D5867 test method was also used in industry to measure the physical properties of cotton fibres using high-volume instruments.

2.2 Yarn Manufacturing

The cotton roving, with 1.0 and 1.3 hanks, was procured from the industry. Single siro yarns were produced by feeding two rovings together, maintaining a 9 mm spacing between them throughout the draft zone on a ring-frame. The Siro spun yarn linear densities of 32.8 and 24.5 tex were produced by keeping the draft 25 by inserting the “S” twist in single and “Z” twist in plied Siro spun yarns with different Twist factors on Siro yarn manufacturer of Goodbrand & Co. Ltd., as shown in Table 1.

Siro-spun yarns were manufactured on Zinser ring spinning M/c using a traveler of 2/0. The first Siro

Table 1 — TF, TPM & Count (Tex) of different plied ring spun Siro yarn

Yarn count & twist factor	18^s Ne (32.8 Tex)						24^s Ne (24.5 tex)		
	TF	TPM	N_{Tex}	TF	TPM	N_{Tex}	TF	TPM	N_{Tex}
Single ply (S1)	3.09	540	32.8	3.67	641	32.8	3.49	705	24.50
Two ply (S2)	2.78	327	72.16	3.30	398	68.88	3.15	439	51.45
Three ply (S3)	2.47	240	106.27	2.93	288	103.32	2.79	299	87.17
Four ply (S4)	2.16	181	141.69	2.57	219	137.76	2.44	240	102.9
Five ply (S5)	1.85	139	177.12	2.20	168	172.2	2.27	218	128.62

** Twist Factor (or TF) = Turns per Meter (TPM) ×√Yarn Count (Tex)* yarn (32.8 tex) was spun at two twist levels, 540 and 641 twists per meter (TPM). The second Siro yarn (24.5 tex) was spun at 705 TPM. The 90% twist level was inserted for two-ply yarns of parents' single-ply yarns, 80% twist level for three-ply yarns,70 % for four-ply yarns, and 60% twist level for five-ply yarns. The specimen length for the plied yarns was kept at 50.0 mm. Twist contraction was considered in the range of 5 to 8 % for Siro spun yarn. The paramount twist tester was used to measure the twist amount of plied yarns, while the Ureka twist tester was used to ply Siro-spun yarns singly. The ASTM D1423 was selected for yarn twist analysis by the StaybridgeTwist Tester[22]. The yarns were scoured at 90 ºC with 40 g/L NaOH and 5 g/L Lisapol N wetting agent for 60 minutes, followed by a cold wash. The scoured yarns were dried at 90 ºC.

2.3.1 Wicking Theory

Wicking height is related to the pore size. Theoretically, the maximum wicking height can be expressed as follows[23]

$$H = 2\gamma \cos\theta / gRs \qquad \text{...(1)}$$

Where,*H*is the maximum wicking height; γ and ρ are the surface tension and density of theliquid, respectively; θ is the advancing contact angle of the liquid to the solid; *g* is theacceleration due to gravity; and *Rs* is the mean static radius of the pores. Eq. (1) states that the wicking height of yarns in a certain period is related to the size of the capillaries and the physicochemical characteristics of the liquid. Increasing the yarn twist level will decrease in *Rs,* and the wicking height, *H,* should increase proportionately.

2.3.2 Yarn Packing Coefficient (μ), Yarn Diameter (d) and Yarn Helix Angle (α)

Yarn diameter affects fabric thickness, air permeability, and aesthetic properties, while packing density determines the compactness of fibreswithin the yarns. The yarn packing coefficient is a measure of how density the fibres are packed within the overall yarn structure. It is calculated as the ratio of the actual volume occupied by the fibres to total apparent volume of the yarn. The packing coefficient is a ratio and is therefore unitless. The packing coefficient values exhibit for spun yarn's in the range from 0.30 to 0.45, while continuous filament yarns can approach 1.0 (perfect packing).

Yarn packing coefficient(μ):Specific volume of fibres (SV_f)/ Specific volume of yarn (SV_y). For cottonfibre, yarn density (ρ) is exist0.9g/cc, so,yarn volume (Vy) is1.1 cc/g (but actual vary with twist).
$SV_y = \pi\,(d/2)^2 \times l / m$; where *l*is length and *m* is mass.

$$(SV_y) = \{\pi(d^2/4)\times 10^5\} \,/\, \text{Tex count} \qquad \text{...(2)}$$

Yarn density = 1/ yarns specific volume (SV_y)
So, Yarn's packing density = Yarn density / fibre density (1.54 for cotton fibre)

This can also be expressed in terms of yarn diameter (d) and yarn linear density (Tex) as :

$$d\ (\text{cm}) = \sqrt{(4 \times Vs \times \text{Weight}) / (\pi \times \text{Length})} \qquad \text{...(3)}$$

$$\text{Yarndiameter } (d_{cm}) \text{: } 0.375(\sqrt{\text{Tex count}})/100 \qquad \text{...(4)}$$

$$\text{Yarn helix angle } (\alpha)\text{: } Tan\ \alpha = \pi dT\ ; \alpha = Tan^{-1}(\pi dT) \qquad \text{...(5)}$$

where, *T* = turns per cm; d = yarn diameter in (cm);*α* = measured angle in degree

2.4 Experimental Work

The Siro plied yarns have a specific bipartite yarn structure, which shows entirely different wicking behaviour. The laboratory-made vertical wicking tester was employed to test the wicking behaviour of Siro yarns similar to YG (B) 871 Pupillometer as per the BS3424 test method, for which a vertical scale was hung, having the lower end in the dye pot as shown in Fig.**1**. The AATCC-197 test method was performed for vertical textile yarn wicking.

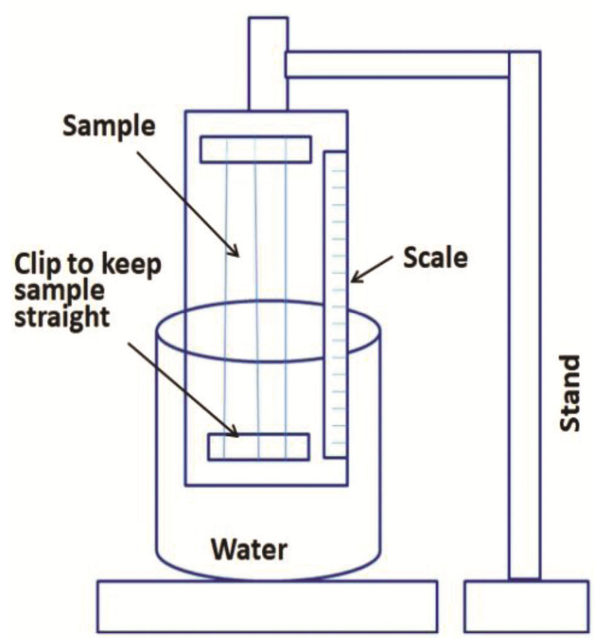

Fig.1 —Test Apparatus for wicking rise in ply Siro spun yarns

Thetesting conditions of the Siro yarn samples were kept according to ASTM D1776 standards. A dead weight was hung to maintain the tension of 0.1 g/tex. A 1% cold brand direct dye was dissolved in the water reservoir to accurately track the wicking height.

2.4.1 Capillary Rise Measurement:

The capillary-rise method was used to test the properties of the Siro spun yarn. Spontaneous wicking occurs owing to capillary penetration, and the absorption height is recorded as a function of time. During the wicking study, the time intervals were chosen as follows: first 30 seconds for 3 minutes, then 2-minute intervals for 6 minutes, and 3-minute intervals for 6 minutes, totaling 15 minutes. The specimen length was kept at 200 mm. It was hung vertically on single, 2-ply, 3-ply, and 4-plied yarns, viz., 1.64g, 5.04g, and 7.15g, respectively. The yarn diameter for all plied Siro yarns was measured on the LICA microscope version (V-2.4). ASTM E1382 test standard was used for image analysis, and the cross-sectional image of yarn diameter was measured by the ASTM E1951 method. The yarn strength and elongation were measured using an Instron tensile testing machine, in accordance with ASTM D2256.

3 Result & Discussion

The wicking behavior of various Siro spun single and ply yarns is given as under in Table 2.

3.1 Wicking Height for 32.8 Tex (3.09 & 3.67)TFPly Ring Spun Siro Yarns

It is observed from Table 2 that two-ply and single-ply yarns reach a maximum wicking height with ranks first (15.03 cm) and second (10.12 cm), respectively, while 5-ply yarn gains the least wicking height (6.5 cm) among these yarns, which may be attributed to the fact that as the number of plies increase, the total amount of wicking water also increases, which climbs against the gravity. The single-ply Siro yarn demonstrated the quickest wicking ability compared to other ply Siro yarns up to 1 minute, which is very close to the double-plied Siro yarn. The single-ply Siro yarn has a TF of 3.09, and the double-ply Siro yarn has a TF of 2.78. The higher number of plies exerts more centripetal force on constituent fibres, which may become the cause of capillary collapse upto some extent.

It is also observed from Fig. 2(a) that more plied yarns exhibited lower wicking height due to the higher volume and diameter of plied yarn. More ply yarn has more open capillaries, but in the case of two-plied yarn, optimum capillaries are produced due to optimum 2.78 TF (327 TPM). Single-ply Siro yarn has a higher TF value of3.09 than other plied yarns, producing more compact capillaries due to more tensile force produced on the yarn surface by twisted sheath fibers, as similarly concluded in a previous study [25].

Fig. 2(b) depicts the vertical wicking height (9.32 cm) for the S2 ply yarn, which is close to the wicking height of S1 (9.12 cm). S1 and S2 plied yarns show a maximum wicking height compared to other plied Siro yarns. It may be due to a higher Twist factor (3.30) i. e., 398 tpm, and the optimum diameter is 499.7, than other plied yarns. The single and two-ply yarns gain the same wicking behaviour due to the

Table 2 — Wicking Behavior for Different Ply Siro-spun Yarns

Time (min.)	0.30	1.00	1.30	2.00	2.30	3.00	5.00	7.00	9.00	12.00	15.00
Ply yarns	(a) – Wicking height (cm) for 32.8 Tex (3.09 TF) ply ring spun siro yarns										
S1	3.14 (14.0)	4.04 (12.8)	4.88 (7.4)	5.45 (5.5)	6.09 (5.7)	6.63 (6.5)	7.37 (6.5)	8.08 (6.9)	8.32 (7.1)	9.24 (6.3)	10.12 (5.3)
S2	3.03 (10.5)	4.03 (5.7)	4.94 (4.8)	5.72 (4.0)	6.30 (3.8)	6.97 (5.4)	8.11 (5.9)	8.97 (6.5)	9.84 (6.6)	10.92(6.3)	15.03 (4.4)
S3	2.80 (10.9)	3.53 (10.2)	4.07 (10.2)	4.52 (5.7)	5.02 (4.6)	5.50 (8.4)	6.26 (4.5)	6.77 (4.6)	7.18 (4.6)	7.88 (3.4)	8.84 (4.5)
S4	2.40 (14.6)	3.07 (14.3)	3.50 (12.6)	3.80 (12.0)	4.00 (11.5)	4.26 (10.5)	4.58 (10.3)	4.92 (10.3)	5.26 (10.1)	5.70 (8.4)	6.20 (7.6)
S5	2.47 (10.9)	3.13 (10.7)	3.50 (9.7)	3.81 (8.3)	4.12 (6.3)	4.30 (6.9)	4.76 (7.9)	5.17 (6.2)	5.54 (6.1)	5.90 (6.3)	6.50 (5.1)
	(b) – Wicking height (cm) for 32.8 Tex (3.67 TF) ply ring spun siro yarns										
S1	2.50 (12.8)	3.38 (7.9)	4.20 (7.6)	4.65 (7.5)	5.09 (8.5)	5.29 (8.8)	5.98 (7.5)	6.76 (8.8)	7.33 (9.1)	8.13 (7.5)	9.12 (6.3)
S2	2.42 (9.5)	3.31 (8.6)	3.91 (7.4)	4.45 (8.5)	4.95 (7.8)	5.42 (7.2)	6.17 (6.9)	6.83 (5.3)	7.44 (4.5)	8.29 (4.2)	9.32 (4.9)
S3	2.56 (9.0)	3.15 (9.2)	3.81 (10.5)	4.28 (8.6)	4.61 (10.2)	4.94 (8.3)	5.37 (8.2)	5.78 (6.9)	6.25 (5.6)	6.75 (5.3)	7.18 (5.6)
S4	2.57 (8.0)	3.28 (7.0)	3.92 (7.6)	4.33 (8.3)	4.60 (6.3)	4.90 (6.9)	5.45 (7.3)	5.88 (7.8)	6.20 (6.9)	6.64 (6.2)	6.94 (5.2)
S5	2.30 (9.9)	2.95 (8.8)	3.37 (6.5)	3.70 (5.9)	3.93 (5.8)	4.20 (5.9)	4.70 (6.8)	5.15 (6.6)	5.61 (6.4)	5.98 (6.0)	6.32 (5.4)
	(c) – Wicking height (cm) for 24.5 Tex (3.49 TF) ply ring spun Siro yarns										
S1	2.60 (13.4)	3.51 (11.1)	4.16 (12.3)	4.72 (10.2)	5.28 (8.5)	5.79 (7.4)	6.55 (7.3)	7.34 (7.1)	7.85 (6.8)	8.48 (8.0)	9.35 (7.1)
S2	2.92 (8.5)	3.90 (6.6)	4.66 (5.6)	5.20 (7.1)	5.82 (7.0)	6.35 (6.9)	7.10 (7.2)	7.81 (4.9)	8.42 (4.7)	9.35 (6.2)	10.46 (5.7)
S3	2.74 (8.9)	3.78 (7.6)	4.41 (7.2)	4.90 (6.9)	5.32 (7.3)	5.79 (7.5)	6.36 (7.8)	6.87 (8.0)	7.47 (8.5)	8.05 (8.6)	8.73 (9.5)
S4	2.42 (8.6)	3.22 (7.8)	3.70 (7.0)	4.20 (5.9)	4.62 (5.8)	5.05 (5.1)	5.46 (4.9)	6.02 (5.3)	6.39 (5.2)	6.86 (4.9)	7.42 (4.4)
S5	2.22 (8.1)	2.91 (7.6)	3.41 (7.0)	3.79 (6.3)	4.15 (4.6)	4.36 (4.6)	4.71 (7.2)	5.23 (8.0)	5.59 (7.3)	6.00 (6.6)	6.43 (4.9)

*C.V(%) is shown in parentheses and brackets

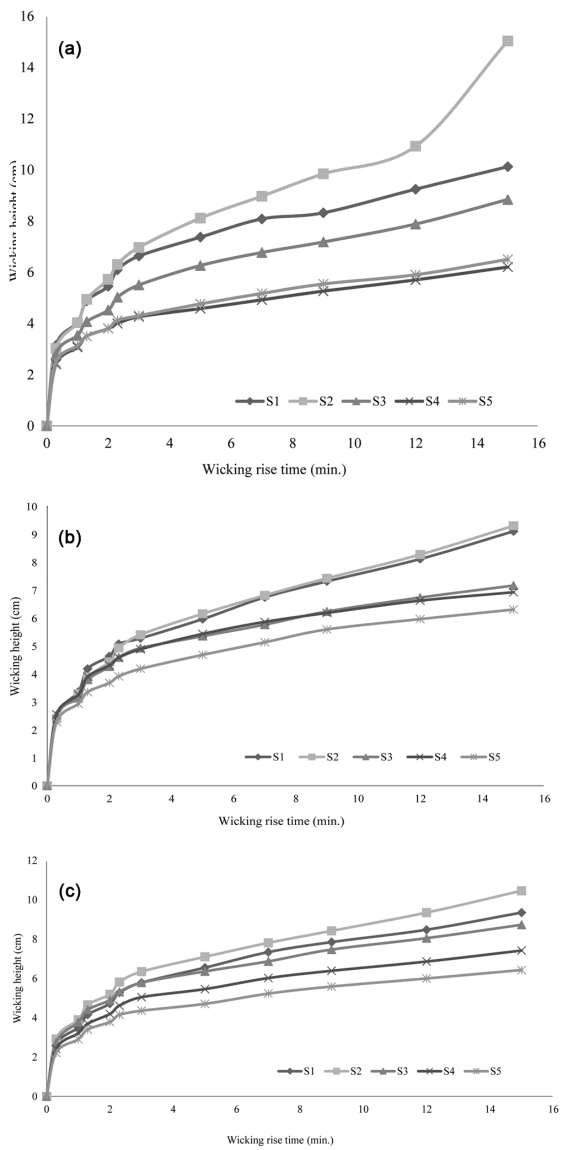

Fig. 2(a) — Plied Siro yarn's wicking behaviour for 32.8 tex (3.09 TF) ply counts,(b)—Plied Siro yarn's wicking behaviour for 32.8 tex (3.67 TF) ply counts (c) — Plied Siro yarn's wicking behaviour for 24.5 tex (3.49TF) ply counts

higher Twist factor , 3.67, than the control yarn TF, 3.09. The three and four-ply yarns demonstrated the same wicking rate, possibly due to the balance between the twist and capillary effect in plied Siro spun yarns. A 5-ply Siro yarn shows a lower wicking rate due to the higher open capillaries of plied Siro spun yarns which is concluded by the researchers as the difference of wicking height between 2-ply cotton ring yarn and higher number of ply yarn gradually decreases from finer yarn to coarser yarn[6].

3.2 Wicking Height for 24.5 Tex and 3.49 TF Ply Ring Spun Siro Yarn

The wicking behavior of 2-ply (51.45 Tex) Siro spun yarns shows a higher wicking height than single-ply yarn, which has a TF value of 3.15 and a maximum wicking height of 10.46 cm. The single and double-ply yarns have a higher wicking height than the 3, 4, and 5 plied yarns. For high plies, the capillary coil angle increases, resulting in a longer path to climb the same height as previously concluded [26]. It was also observed by the researchers as highest wicking potential is achieved in case of intermingled warp and textured weft polyester yarns combinations[26].

The ANOVA test results were calculated for different yarn linear densities, TF& plied ring spun Siro yarns. In these experiments, 44 observations were recorded, yielding mean and standard deviation values. Analysis of variance (ANOVA) R^2 values indicate a strong relationship between dependent and independent variables. The F-test value indicated a higher likelihood, and the observed difference is genuine and not due to chance. The F-value of the wicking experiments falls within the range of $F_{critical}$ (2.06) < F_{actual} (14.26 to 59.34), which is highly significant. The P-values for this experiment are highly significant (P-value <0.0001<0.05)ata 95% confidence level.

Fig. 3a, 3b, and 3c show the predicting and in-predicating relationships between the dependent

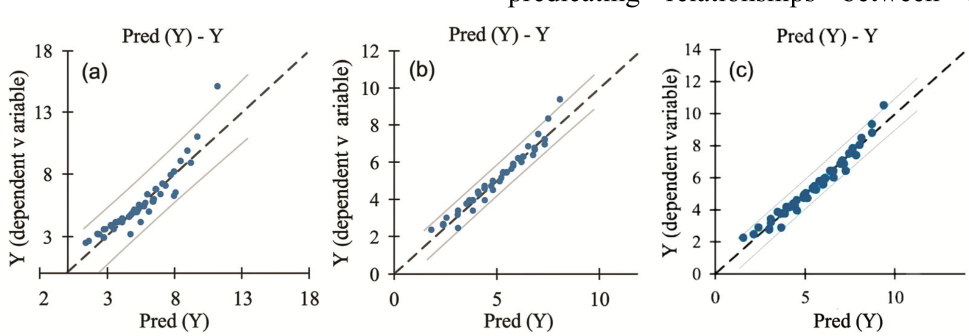

Fig. 3 — Linear regression curve: (a), (b) & (c) using least squire method between dependent variable (Y) and independent variables (X= Pred (Y).

variable (Y) and the independent variable Pred. (Y). R2 values indicate a highly strong relationship between variables. A high number of data points exist between these lines, which leads to a better understanding. In contrast, a few data points fall outside these lines, which warrants a 95% confidence level. The curves 3(b) & 3(c) yielded values of R2 = 0.95 and 0.96, respectively, demonstrating a stronger relationship between variables than the curve 3(a) value of 0.867.

Fig. 4a, 4b, and 4c exhibit the relationship between average wicking height and wicking rise time. Figure 4a shows a better average wicking height than 4b and 4c, which may be due to optimum capillary action found between these plied siro yarns. Figures 4b and 4c show lower wicking heights of 9.12 and 9.32 cm, respectively, due to the capillary collapse within different ply ring spun siro yarns.

3.3 Wicking Behaviors for 2-Ply, 3-Ply, 4-Ply & 5-Ply Siro Spun Yarns at Different TF Values

There is a notable contrast in the wicking rates between single-plied and more plied Siro-spun yarns. The wicking rate falls due to the larger capillary pore size in the more plied yarns. This variability in wicking behaviour is higher in the case of single-plied yarn than in the case of multiplied yarn, as shown in Fig. 4 and Fig.5. More plied yarn, with its higher void space between fibre layers, and among the fibres, creates a loose capillary effect between the fibre layers. Three-ply and four-ply yarns with a structure resembling high-voluminous yarn and greater free space between fibre layers exhibit a similar effect in wicking height and wicking rate[6].

It is observed from Fig.5(a) that the yarn of TF 3.09 single-ply yarn shows higher wickability (10.12 cm) than the TF of 3.67 yarn, which showed wicking height of 9.12 cm for a 32.8 tex yarn linear density. Intermediate values of wicking heights of 9.35 cm are observed at a TF of 3.49 with a 24.5 tex count coarser yarn, as similarly concluded in a previous study[8]. It shows that a higher TF reduces wickability by reducing the capillary size between staple fibres. The wickability of 2-ply yarns also follows the same trend as single-ply yarns, which is shown in Fig. 5(b). Based on the TF of 3.30 value, the yarns showed higher wicking height (15.03cm) than the 3.15 and 2.78 TF value Siro spun yarn. It is mainly due to the higher amount of inserted twist (TF) that increases the wickability of these yarns, as presented in curves.

Based on the above analysis, Fig.5 (c) depicts the wicking height for 3.09 TF base 3-ply yarns at various

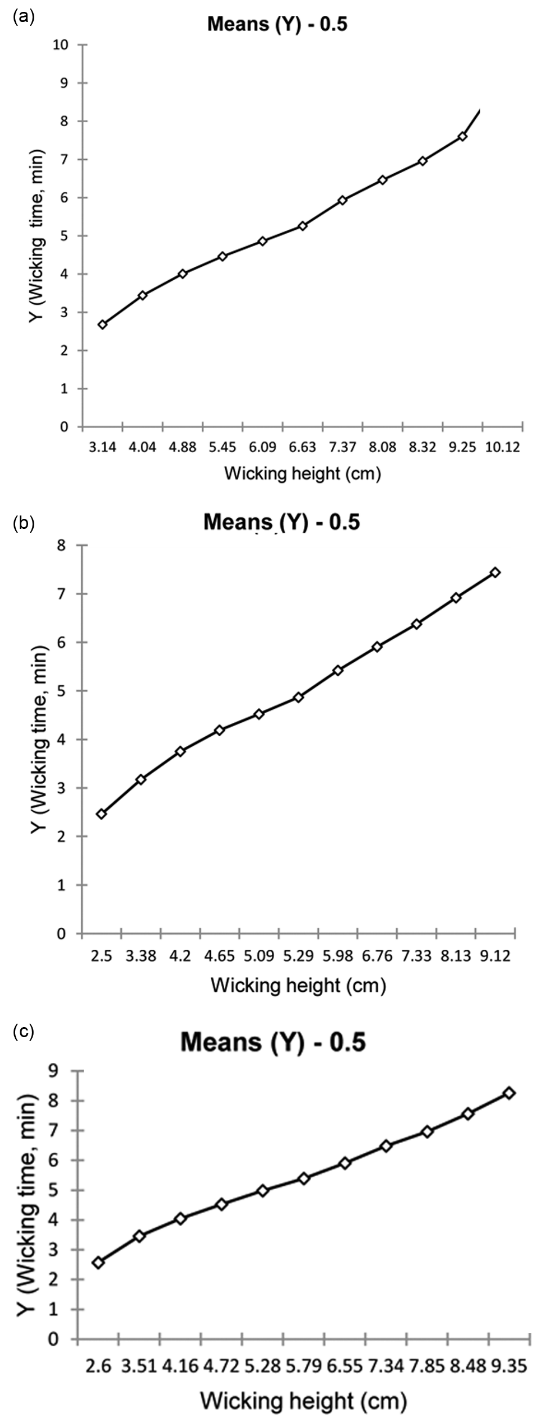

Fig.4 — Linear regression curve : (a), (b) & (c) using least squire method between dependent variable (Y) and independent variables (X= Pred (Y)

time intervals. While 4-ply siro spun yarns show an opposite trend for wicking behaviour, in which the lower TF value ply yarns are found to have lower wicking height than higher TF yarns, which is mainly

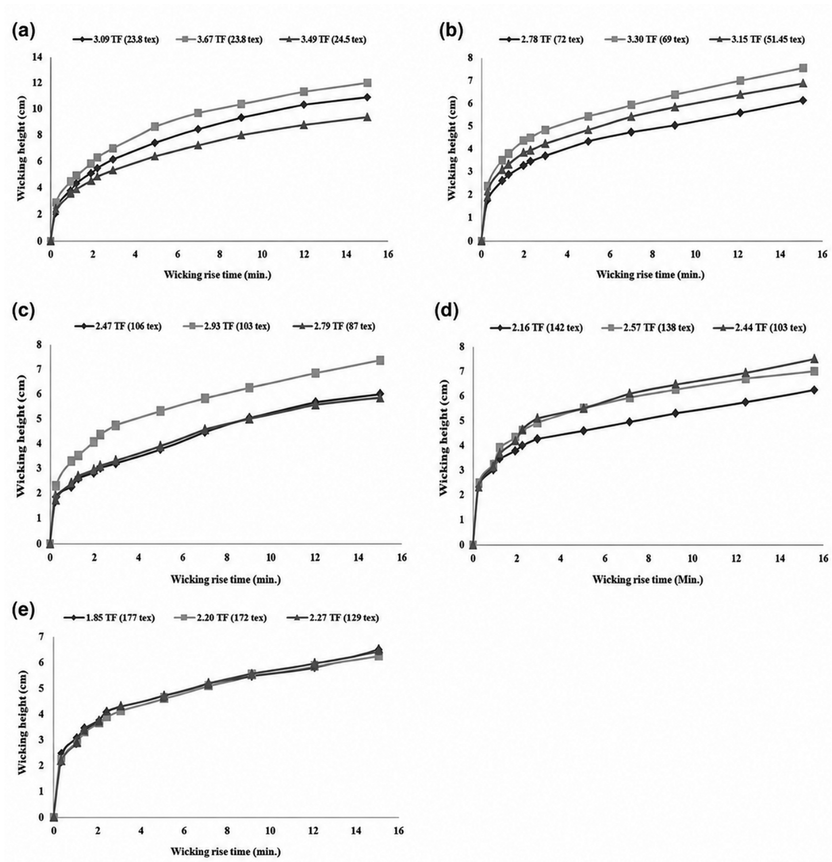

Fig. 5(a) — Single plied Siro yarn's wicking behavior varies with TF values and ply counts,Fig. 5(b) — Two plied yarn's wicking behaviour varies with TF values and ply count,Fig. 5(d) — Four plied yarn's wicking behaviour varies with TF value and ply count. Fig. 5(e) — Five plied yarn's wicking behavior varies with TF values and ply counts

due to the higher amount of yarn diameter presented in the 2.16 TF single ply yarns. Fig.5e shows a specific trend for 5-ply Siro spun yarns, where the wicking height and wicking rise time values are exhibited, demonstrating the merged effects, which may be due to a higher diameter, showing a mixed trend of capillary channel size in all twist levels of plied yarns[6].

The ANOVA test results are presented the total number of observations for each plied yarn is 22, and the mean values and standard deviation of each ply are, respectively, (4.41-6.65) and (1.27-2.72).

R^2 (analysis of variance) values are observed in the range of (0.995 to 0.999), which shows a high strength of the relationship between variables at the 95% confidence level. The F-value of wicking experiments is shown to be within the range of F critical (2.94) < F_{actual} = (73.71 to 723.04). The F-test results indicate a higher F-value and therefore a higher likelihood that the observed difference is genuine and not due to chance. The P values for the wicking experiment are observed (P-value<0.0001<0.05), which is highly significant at a 95% confidence interval.

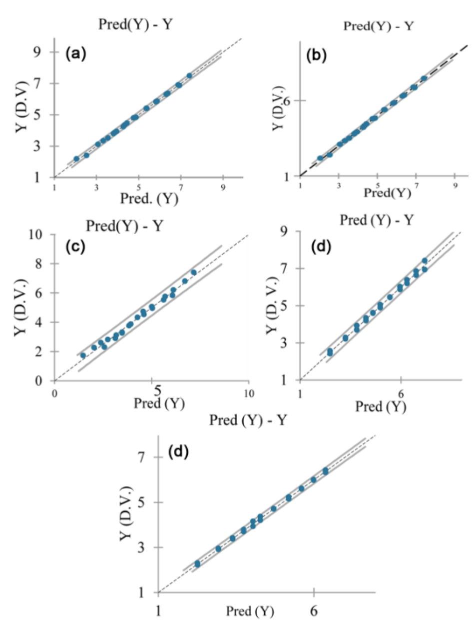

Fig. 6 — Linear regression curve : (a), (b), (c), (d) & (e) using least squire method between dependent variable (Y) and independent variables, X= Pred (Y).\

This linear regression curve illustrates the predictive relationship between dependent and independent variables.The linear curve shows that the dependent variable (Y-axis) increases linearly with the predicting variable Y. The analysis of variance yields a higher F-value at 95% confidence intervals, indicating a higher likelihood that the observed difference is real and not due to chance. Figures 7 (a), 7(b), and 7(c) shows the relationship between the independent variable Y (Time) and the dependent variable X (wicking height, cm), showing that the wicking height increases with time. It shows significantly increased mean wicking heights from 25 mm to 108 mm, which may be due to the higher TF and coarser Siro spun yarns. Figure 7(a) and 7(c)

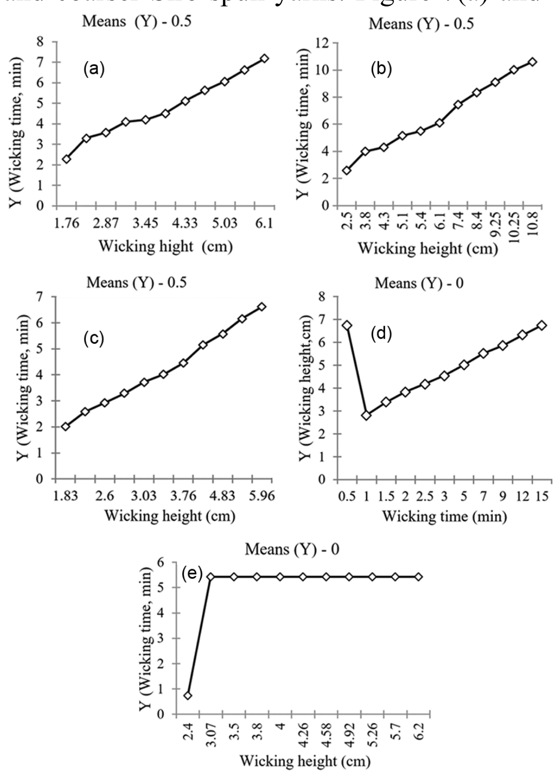

Fig.7 — Linear regression curve: (a), (b), (c), (d) & (e) using least squire method between dependent variable (Y) and independent variables (X= Pred (Y).

show the mean wicking height (1.76-6.10 cm) and (1.83-5.96 cm), respectively. Figure 7(d) and 7(e) show the mean wicking height in a narrow range, mean wicking height (2.9-6.9

3.4 Effect on Tenacity and Extension for Different Ply Siro Spun Yarns

Table 3 shows that low-twist linear-density yarn has a higher tenacity value than higher linear-density yarn. Higher TF shows greater tenacity by maintaining a constant linear density, which may be due to a higher fibre-to-fibre contact area. Higher-plied yarn shows higher tenacity than lesser-plied yarn, possibly due to lower cohesive force between the fibres of the lesser-plied yarn. The higher-plied yarn has higher tenacity in each observation due to greater fibre friction between the fibre layers of the plied yarn with constant TF. The yarn wicking performance was significantly affected by the applied tension and the twist level in yarn 3i.e.(24.50 tex). The twist level in higher-plied yarns influences the size of the individual fibre capillaries and the decrease in the capillary space[27]. The yarn extension increases with an increasing number of plies in Siro yarn. For the constant number plied yarn, low linear yarn density has a higher extension than high linear density yarn. However, three plied Siro yarns show an inverse order in extension values. The higher-plied yarn has greater extension due to more void spaces between the fibres of the plied yarn.

The higher the void space between the fibre layers, the lesser the capillary effect, resulting in a lower wicking height and wicking rate, as similarly observed in the wicking behaviour in stretched single and plied elastic yarns owing to an increase in the interfibre pore size[28].

3.5 Effect of Yarn Diameter (Volume),Helix Angle (α) and Packing Coefficient (μ) on Wicking Behavior for Different Ply Siro Spun Yarns

It is clear from Table 4 that a higher number of yarn plies results in a higher volume or diameter. In

Table 3 — Tenacity (cN/tex) and extension (%) values of different ply Siro-spun yarns.

Yarns count	32.8 tex (3.09 TF)		32.8 tex (3.67 TF)		24.50 tex (3.49 TF)	
Plied yarns	tenacity	extension	tenacity	extension	tenacity	extension
S1	16.58 (7.72)	6.08 (7.82)	18.99 (7.38)	6.59 (12.1)	26.58 (7.64)	7.01 (7.41)
S2	16.82 (7.79)	6.86 (5.24)	19.24 (8.76)	7.58 (14.1)	26.72 (5.79)	7.82 (3.81)
S3	17.88 (5.51)	8.08 (6.06)	19.60 (3.9)	7.94 (11.0)	27.04 (11.52)	7.85 (11.14)
S4	18.59 (8.60)	8.73 (5.7)	20.57 (5.2)	8.99 (3.6)	27.74 (4.03)	9.83 (4.75)
S5	18.92 (4.70)	9.00 (5.66)	20.87 (4.46)	9.74 (1.81)	28.36 (5.10)	10.47(3.72)

*CV values are shown in parentheses brackets

Table 4 — The characteristics of plied yarns density (g/cm^3) in measured and calculated terms

Plied Siro spun yarns	32.8 tex (3.09 TM)		32.8 tex (3.67 TM)		24.5 tex (3.49 TM)	
	measured	calculated	measured	calculated	measured	calculated
S1	0.375	0.912	0.437	0.912	0.912	0.912
S2	0.309	0.909	0.352	0.907	0.913	0.912
S3	0.374	0.909	0.423	0.906	0.906	0.906
S4	0.466	0.907	0.516	0.906	0.908	0.907
S5	0.542	0.906	0.554	0.906	0.907	0.907

Table 5 — Plied Siro spun yarns helix angle (α), packing coefficient (μ) and diameter, d (μm)

Plied Siro yarns	32.8Tex (3.09TM)			32.8Tex (3.67TM)			24.5Tex (3.49TM)		
	α	μ	d	α	μ	d	α	μ	d
S1	29.23	0.243	333.80	31.87	0.283	309.41	32.42	0.592	287.38
S2	29.23	0.201	545.17	31.94	0.228	499.75	31.75	0.592	449.62
S3	24.36	0.243	601.38	26.77	0.274	558.81	25.19	0.588	501.50
S4	19.46	0.302	621.89	21.84	0.335	583.05	22.29	0.589	544.20
S5	15.72	0.352	645.78	18.35	0.359	629.98	21.26	0.589	589.67

* Yarn packing coefficient = fibre volume/yarn volume

this case, the same number of ply yarns exhibited a decreasing trend of volume due to a higher amount of TF present in the spun yarns, which is compacting the yarn structure by collapsing the free space among the constituent fibres, as similarly observed in the case of polyester filament yarns[28]. The higher wickabilityof Siro ply yarns is presented by lower voluminous (diameter) and optimum TF (TPI). Higher volumes of yarns (lower yarn density) exhibit larger pore sizes in the more plied yarns, which creates a lower wicking height. The wicking potential of cotton yarn was reduced by an increase in twist level [29].

The present study investigates the impact of helix angle (twist angle), packing coefficient, twist coefficient, and linear density on the wicking behaviour of yarn. Table 5 shows that a higher helix angle, α (29 to 32), with a lower packing coefficient μ (0.20 to 0.28) yarn, exhibits a higher wicking height than other plied Siro yarns, as similarly reported in a previous publication[12].24.5 Tex (3.49TM) based yarn observed higher packing density (0.58 to 0.59) showed lower wicking height due to more compact structure of these plied yarns. The two-ply yarns exhibited optimal capillary space, due to lower packing coefficient, μ = (0.20 to 0.23) and higher helix angle, α = (29 to 32) for the wicking phenomenon. Ahmmed & Delele . (2024) indicated that the highest to lowest wicking length and rate were found in the treated yarn bundles, treated fabric layers, untreated yarn bundles, and untreated fabric strips, respectively[24].

Lu, Yuzheng*et al.* [10] demonstrated that as the twist coefficient decreases, the wickingheight increases with decreasing yarn compactness. Two plied yarns exhibited the lowest packing coefficient (0.22 to 0.24) among other plied yarn structures, which creates an optimal capillary for water wicking behaviour,as similarly reported for a smaller diameter with less space within the inter-fibres and a negative relationship was established between wickability and packing density [27].

The effect of yarn linear density and TPM on wicking rate and height is shown in Table 1. For yarns with constant linear density, the higher TPM yarns exhibit a lower wicking rate and wicking height, likely due to the compact capillary created by the higher twist. Conversely, lower linear density yarns show slightly higher linear density and wicking height, which can be attributed to the fine capillaries in the fine yarn count. As depicted in Fig. 2(a), lower TF in Siro-spun yarns results in higher wicking height and rate, while higher TPM Siro yarns (with constant yarn linear density) have lower wicking height and rate.

The effect of TF, yarn linear density on wicking behaviour is shown in Fig. 2. The three-ply Siro yarn with TF 3.06 has a lower wicking height, and the wicking rate decreases as the TF is reduced to 2.29. Siro spun yarns with a lower TF value have a higher wicking rate and height due to the apparent capillary effect, as shown in Fig. 2a. The fine yarn has a lower wicking height and wicking rate than other yarns with different linear densities.

The four-plied Siro yarn with a lower TF, 2.39 TF yarn has a lower wicking height and wicking rate than a higher TF value for the constant linear density yarn, as shown in Fig. 3d. The fine linear density Siro yarn, on the other hand, shows a higher wicking rate and wicking height.

3.6 Effect of Siro Yarn Structure on Wicking Potential

The images of 100% cotton plied siro spun yarns are shown in Fig. 8, indicating the yarn diameter and

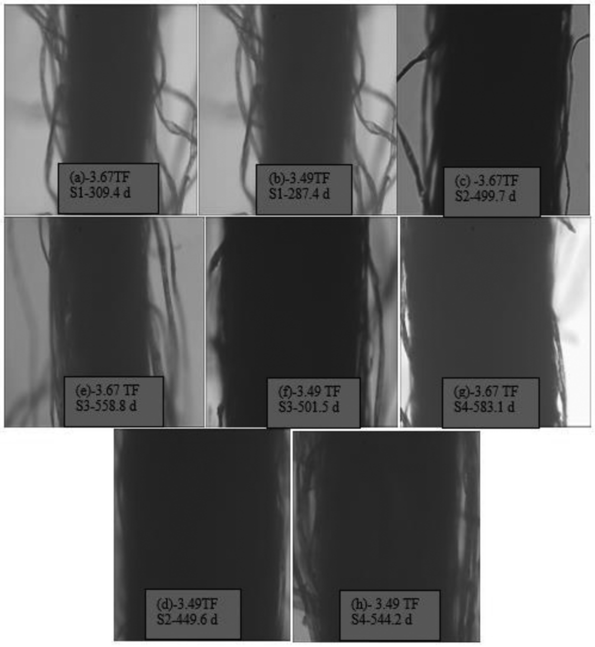

Fig.8— Plied Siro spun yarn's diameter images (a), (b), (c), (d), (e), (f), (h) were captured on LICA scanning microscope (version-2.4), *Yarn ply values are shown in fig.8 as S1(1-ply), S2 (2-ply), S3(3-ply) & S4 (4-ply)

inter-fibre structure within the plied siro yarns. The plied siro yarn with TF of 3.67 shows optimum capillaries compared to the TF of 3.49 plied yarn. The 32.8 tex plied siro yarn with TF of 3.67 showed a higher diameter with optimum capillaries than the coarser yarn linear density 24.5 tex (3.49TF) plied siro yarns. The 24.5 tex plied yarns showed a compact yarn packing coefficients(μ= 0.58 to 0.59), which exhibited lower wicking height than the 32.8 tex plied yarn, as compact Siro spinning of polyester yarn[10]. An increase in yarn roughness due to the random arrangement of constituent fibres decreases the rate of water transport, which may depend on the factors related to water transport by a capillary process. The effective advancing contact angle of water on the yarn increases with increasing yarn roughness. The random distribution of constituent fibres in the yarn reduces the continuity of capillaries. The 2-ply siro spun yarn observed the same twist direction as the S-twist, which shows a more apparent trend than single-ply, 3-ply, 4-ply, and 5-ply yarns.In 3-ply Siro spun yarns, the structure features a Z-twist in the opposite direction, providing greater resistance for wicking.

4.0 Conclusion

The effects of varying the number of Siro yarn plies, yarn linear density, and twist factor on wicking behaviour, an essential aspect of engineering in high-comfort fabrics for different seasons, have been explored. Siro spun yarns have dominated both compact cotton and plied ring-spun yarns to achieve the highest wicking potential. Yarn tenacity was found to increase with an increase in yarn linear density. The wicking height of 24.5 tex double-ply Siro yarn was 10.46 cm. Double-ply Siro yarn with TF 3.09 offered a maximum wicking height of 10.12 cm after 15 minutes. Increasing TF decreases the wicking height across all yarns. As the number of plies in Siro yarn increases, the wicking height and the wicking rate both decrease. Increasing TF decreases the wicking height and wicking rate of different linear-density Siro-spun cotton yarns. The linear densities of cotton Siro-spun yarns also influenced the wicking behaviour. The Wicking height and wicking rate decrease as the yarn fineness increases.

Two-ply Siro spun yarns obtained the maximum wicking height and wicking rate among two to five plied Siro spun yarns. Five plied Siro spun yarns found the lowest wicking height of 2.22 cm (22.2 mm) due to a higher voluminous pore yarn structure. The twist factor and yarn linear density significantly affect the wicking height and rate of Siro spun plied yarns. Single plied Siro spun yarns obtained 2nd position in wicking height and rate compared to other plied Siro yarns. Two plied Siro spun yarn observed maximum wicking height with TF of 3.30 and linear density of 69 Tex, while single ply Siro spun yarn gained maximum wicking height and rate at the value of 3.67 TF and 32.8 Tex. The optimum value of TF (3.67) was observed for 30.8 Tex single-ply Siro spun yarn, while 24.5 Tex Siro spun yarn showed 3.49 TF. Finer yarn count and lower TF exhibited lower wicking height and rate.

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