



Research Article

Development and Characterization of Sustainable Tri-Blend Yarn from Eco-Viscose, Recycled Cotton, and Modal

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KEYWORDS

Eco-Viscose;
Circulose; Ecovero;
Sustainable yarn;
Recycled cotton

ABSTRACT

Textile industries in Bangladesh are increasingly moving toward eco-friendly fibers because of rising environmental awareness, stricter regulations, higher raw material costs, and growing demand for sustainable clothing. In this study, a sustainable tri-blend yarn was developed by using eco-viscose, recycled cotton, and modal. The eco-viscose was produced from a mix of Circulose and Ecovero pulp. Circulose is made from recycled textile waste and Ecovero comes from certified renewable wood sources. Virgin cotton was fully replaced by recycled cotton. Due to lower strength of recycled cotton, a small amount of modal was added to improve yarn strength and performance. Seven different blend ratios were selected using Minitab's extreme vertices design. The samples were tested using the USTER Evenness Tester and Lea Yarn Strength Tester. The results showed that blends containing about 20% recycled cotton provided the optimum balance between yarn quality and strength performance. Blends containing up to 25% recycled cotton produced acceptable yarn properties and can be recommended for knitting applications without significant deterioration in yarn quality.

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1. Introduction

The textile industry is rapidly adopting sustainable materials. This shifting is getting faster because nowadays people are more aware of environmental issues, governments are employing stricter rules, and the cost of virgin raw materials is rising [1], [2]. On the other hand, customers also want clothing that is safer for the planet. This encourages manufacturers to search for sustainable fiber options. From this thinking, many spinning mills are now experimenting with recycled fibers and eco-friendly regenerated cellulosic fibers.

Considering this, eco-viscose fibre has gained strong attention. It is made from wood pulp but uses cleaner and more sustainable production methods than regular viscose [3]. In this study, eco-viscose derived from a mix of Circulose and Ecovero pulp. Circulose is obtained from old garments and textile waste [4]. This helps to reduce landfills and supports a circular economy. Ecovero pulp is obtained from certified and renewable wood

resources. So, it has a smaller environmental impact. When these two pulps are blended, they offer a good balance of sustainability and performance [4], [5].

Recycled cotton, nowadays getting much more importance in yarn production, is widely recognized as a sustainable alternative to virgin cotton due to its environmental and economic benefits. Large amounts of cotton waste are created each year. Recycling this waste helps to save water, land, and energy. However, recycled cotton has some limitations. The fibers are usually shorter, weaker, and sometimes contain impurities [6]. Due to these drawbacks, spinning of recycled cotton is more difficult. It can reduce yarn strength. Because of this, recycled cotton needs support from stronger fibers.

Modal fiber is a high-quality regenerated cellulosic fiber. It is known for its good strength, uniformity, and smooth texture [7], [8]. Adding modal with recycled cotton can improve yarn perfor

mance and help to overcome problems caused by shorter recycled fibers. Therefore, a tri-blend yarn made from eco-viscose, recycled cotton, and modal is a better choice. Which enables both sustainability and quality.

Although sustainable fibers are widely used, research on tri-blend yarns using mentioned fibers is still limited. Most studies focus on only two fibers at a time, such as cotton–viscose or cotton–modal blends [9], [10]. Even when recycled cotton is used, it is usually mixed with virgin fibers rather than with advanced eco-viscose types like Circulose- or Ecovero-based viscose. Another issue is that many studies do not use strong statistical methods to design blend ratios. As a result, it is difficult to understand how different fibers interact and how to choose the best blend for performance.

This lack of research creates a clear gap. There is a need to discover how eco-viscose, recycled cotton, and modal can be combined with different percentages to produce acceptable quality of yarns. It is also important to produce these blends by using a proper mixture design so that all fiber interactions are considered. Without this knowledge, industry personnel may hesitate to adopt sustainable fibres. But they have the potentiality to reduce environmental impact.

To address this gap, the present study carried out to develop seven different ratios of tri-blend yarns. Eco-viscose (made from a 30/70 mix of Circulose and Ecovero), recycled cotton, and modal fibre were used to conduct the study. Virgin cotton is progressively substituted with recycled cotton to improve environmental sustainability and reduce the consumption of natural resources in yarn manufacturing. Modal is added in small amounts to improve strength and overall yarn quality. Seven

different blend ratios were selected using Minitab's extreme vertices mixture design. This method helps identify the best possible combinations of the three fibers. Minitab is a statistical software used to do different statistical analysis.

The seven yarn samples were produced under standard spinning conditions and tested using the USTER Evenness Tester and Lea Yarn Strength Tester. These tests measure important quality indicators such as evenness, imperfections, hairiness, and count strength product (CSP) [11], [12]. The results show that blends with around 20% recycled cotton provide a good balance of sustainability and performance. Even blends with up to 25% recycled cotton remain suitable for knitting applications.

This research provides useful guidance to spinning industries, as they are looking to shift toward circular economy and want to adopt with eco-friendly materials. The findings support this study that recycled cotton and eco-viscose fibre can be used successfully in commercial yarn production without compromising yarn quality and performance.

2. Materials and Method

2.1 Materials

The study used three main fiber components: recycled cotton, eco-viscose, and modal fibers. The physical properties of these fibers were characterized using the Uster High Volume Instruments (HVI) and Premier aQura² Advanced Fiber Information System according to the ASTM D5866-05 method. The detailed properties of the constituent fibers are presented in **Table 1**.

Table 1: Properties of Recycled Cotton, Eco-viscose, and Modal Fiber

Parameters	Recycled Cotton	Eco-viscose	Modal
Length or Upper Half Mean Length (UHML) (mm)	24.3	38	38
Uniformity Index	63.5	-	-
Fineness (dtex)	1.77	1.33	1.3
Short Fiber Content (SFC)% (< 12.7 mm)	41.8	-	-
Tenacity (cN/tex)	18.5	23.4	36
Elongation (%)	7.0	17.3	14
Moisture Regain (%)	8.5	11.5	11.2

Note: Uniformity Index and Short Fiber Content were measured only for recycled cotton using HVI. Properties of eco-viscose and modal fibers were obtained from supplier technical specifications.

2.2 Experimental Design and Blending

employed to investigate the synergistic effects of the three fiber types on the final yarn properties. The blend ratio of the three components-recycled cotton, eco-viscose, and modal -was varied across seven experimental runs. The blend proportions for each experimental run are given in **Table 2**.

Table 2: Proportion of Mixture Component for Seven Experimental Runs

Exp. No.	Recycled Cotton%	Eco-viscose%	Modal%
1	28.33	43.33	28.33
2	30	40	30
3	20	50	30
4	28.33	48.33	23.33
5	30	50	20
6	26.66	46.66	26.68
7	23.33	48.33	28.33

2.3 Preparation of Yarn Samples

To get yarn samples based on the proportion mentioned in Table 2, precise amounts of recycled cotton, eco-viscose, and modal fibers were weighted using an electronic balance to create around 15 kg mixture. This mixture was designed to produce at least 10 rovings, each weighing over 1 kg, ensur-

ing an adequate amount of yarns for testing and fabric sample production. The fibers were then laid down, thoroughly hand-mixed, and conditioned at ambient temperature for at least eight hours.

Table 3: Process parameters of yarn manufacturing

Process	Delivery Materials	Production/Speed
Blow-Room	Card mat: 590 ktex	800 kg/hr: Chute feed to card
Carding	Card Sliver: 90 grain/ yds	55 kg/hr
Breaker Draw Frame	Drawn Sliver: 75 grain/ yds	550 m/min (6 doubling)
Finisher Draw Frame	Drawn Sliver: 75 grain/ yds	550 m/min (8 doubling)
Simplex	Roving: 0.8Ne (TPI 0.85)	950 rpm (Flyer speed)
Ring Frame	Yarn Count: 30 Ne (19.68 Tex) (TPI 20.20)	15000 rpm (Average spindle speed)
Autoconer	-	950 m/min

After that the blended fibers were processed through the blow room and fed into the carding machine via chute feed. The resulting carded slivers were gone to two stages of equalization: first, in the breaker draw frame (by 6 doubling) and then in the finisher draw frame (by 8 doubling). The blending of recycled cotton, eco-viscose, and modal fibers occurred initially through manual mixing, followed by blending in the blow room, carding, and two draw frame machines. This enables a homogeneous fiber blend was achieved in the finisher draw frame. The finisher-drawn slivers were fed to the Simplex machine to produce rovings. The rovings were then fed into the creels of the ring-spinning frame and 19.68 Tex yarn was produced. In this way, seven yarn samples with different blend ratios obtained from seven experimental runs (as mentioned in Table 2) were produced. The process parameters were summarized in Table 3. The processing stages involved in the production of the tri-blend yarn are illustrated in **Figure 1**.

2.4 Characterization of Yarns

The mass variation of yarns was expressed as the coefficient of variation (CVm%), while the imperfection index (IPI) represents the total number of thick places (+50%), thin places (-50%), and neps (+200%) per 1000 m of yarn. The CVm%, IPI, and yarn hairiness were evaluated using the Uster® Tester 6 (UT 6, Uster Technologies, Switzerland). Prior to testing, all samples were conditioned under a relative humidity of $65 \pm 2\%$ and a temperature of $27 \pm 2^\circ\text{C}$ (for tropical regions) following ASTM D1776/D1776M 15 standard. Yarn strength is measured as count strength product (CSP) by lea yarn strength tester.

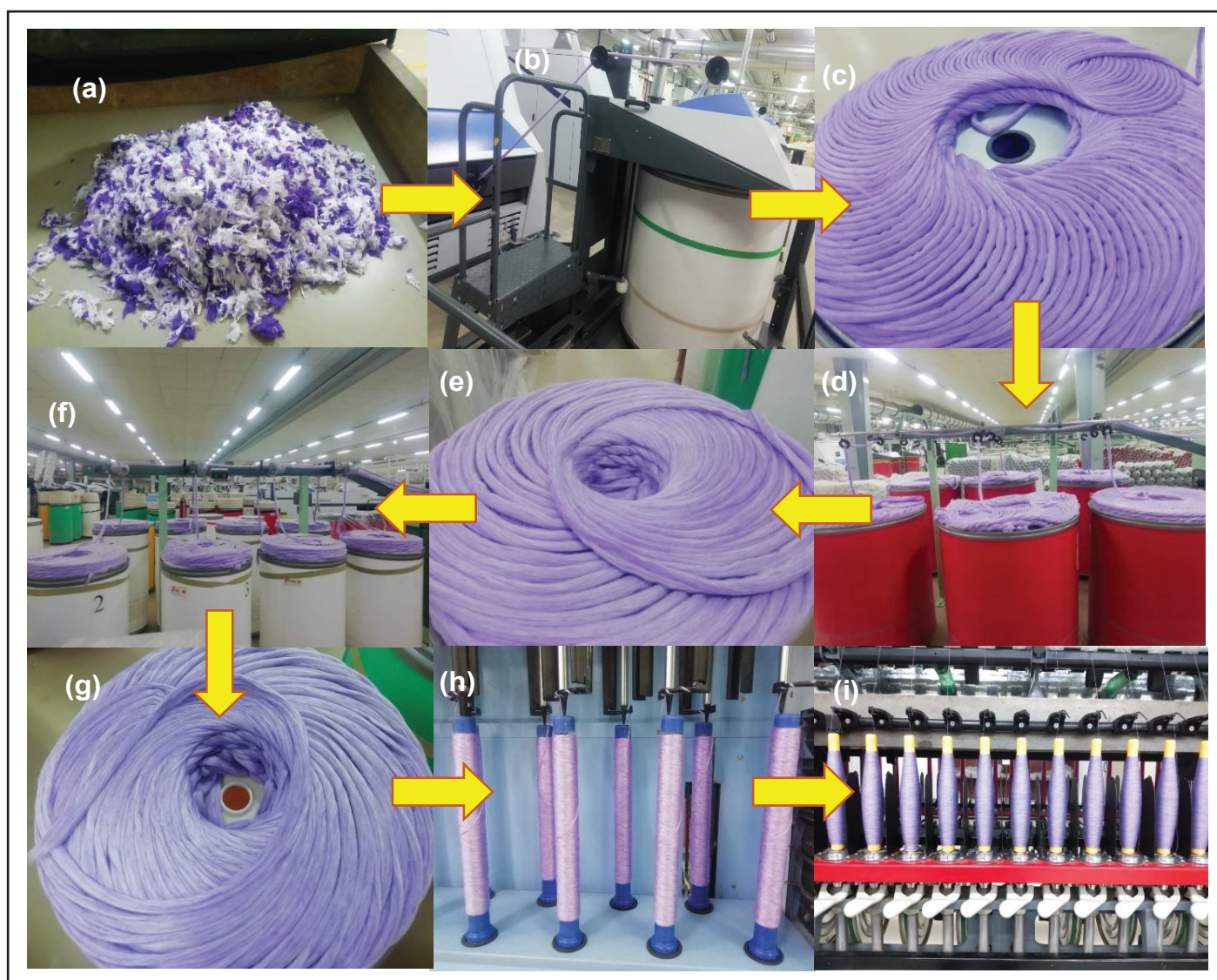


Figure 1: Processing stages of tri-blend yarn production: (a) fibre mixing, (b) carding machine, (c) card sliver, (d) breaker draw frame, (e) breaker drawn sliver, (f) finisher draw frame, (g) finisher drawn sliver, (h) roving, and (i) ring cops.

3. Results and Discussion

Each yarn underwent laboratory testing, and the results for CVm%, IPI, hairiness, and CSP are shown in **Table 4**.

Table 4: Response data of seven experimental run

Exp. Run	(Rec. Cotton)	(Eco - viscose)	(Modal)	(CVm%)	(IPI)	(Hairiness)	(CSP)
1	28.33	43.33	28.33	16.16	657	5.56	2144
2	30	40	30	16.93	933	5.75	2150
3	20	50	30	14.74	268	5.40	2295
4	28.33	48.33	23.33	16.83	853	5.65	2126
5	30	50	20	16.82	858	5.78	2092
6	26.66	46.66	26.68	15.79	568	5.55	2120
7	23.33	48.33	28.33	15.71	516	5.50	2203

3.1 Statistical Interpretation of Blend Composition Effects on Yarn Properties

The relationship between fibre blend composition and yarn quality parameters was evaluated using regression analysis. The statistical performance of the developed regression models is presented in Table 5. The coefficient of determination (R^2) values ranged from 89.25% to 89.48%, indicating that the developed models explained a large proportion of the variability in yarn properties. The relatively small standard error values further indicate good agreement between experimental and predicted values

Table 5: Summary of Model Fit Statistics for Mixture Design Regression Models

Yarn Property	Model Type	Standard Error (S)	R^2 (%)
CVm%	Linear	0.3447	89.48%
IPI	Linear	108.35	89.25%
Hairiness	Linear	0.0631	89.28%
CSP	Linear	30.91	89.47%

The regression equations describing the relationship between fibre blend composition and yarn properties are presented in **Table 6**. The coefficients indicate the relative influence of recycled cotton, eco-viscose, and modal fibres on yarn characteristics. Negative coefficients observed for CVm% and IPI

indicate that increasing regenerated fibre content improves yarn regularity, whereas positive coefficients observed for hairiness and CSP indicate a strengthening effect of modal and eco-viscose fibres on yarn performance.

Table 6: Regression equations

(CVm%)	= 1647 - 16.2 (Rec. Cotton) - 16.4 (Eco-viscose) - 16.4 (Modal)
(IPI)	= 185828 - 1808 (Rec. Cotton) - 1867 (Eco-viscose) - 1869 (Modal)
(Hairiness)	= -495 + 5.03 (Rec. Cotton) + 5.00 (Eco-viscose) + 4.99 (Modal)
(CSP)	= -63315 + 643 (Rec. Cotton) + 657 (Eco-viscose) + 662 (Modal)

The statistical significance of the regression models was evaluated using analysis of variance (ANOVA), and the results are summarized in Table 7. The regression models showed moderate to strong explanatory capability for all yarn properties. The CVm model was statistically significant at the 95% confidence level ($p < 0.05$), confirming that blend composition has a significant influence on yarn evenness. The regression models for IPI, hairiness, and CSP showed near-significant behaviour ($p \approx 0.05$ – 0.06), indicating that fibre blend composition has a noticeable influence on yarn imperfections, hairiness, and strength.

Since the mixture design consisted of unique blend compositions without replication, lack-of-fit statistics could not be calculated. Therefore, model adequacy was evaluated using R^2 values and ANOVA significance tests

Table 7: Analysis of Variance (ANOVA) for Regression Models

Yarn Property	Source	DF	Adj SS	Adj MS	F-value	P-value
CVm%	Regression	3	3.4739	1.1580	9.74	0.047
	Error	3	0.3565	0.1188	–	–
	Total	6	3.8304	–	–	–
IPI	Regression	3	298482	99494.1	8.48	0.056
	Error	3	35217	11739	–	–
	Total	6	333699	–	–	–
Hairiness	Regression	3	0.09954	0.03318	8.33	0.058
	Error	3	0.01195	0.00398	–	–
	Total	6	0.11149	–	–	–
CSP	Regression	3	24929.5	8309.8	8.70	0.054
	Error	3	2866.3	955.4	–	–
	Total	6	27795.7	–	–	–

3.2 Fibre Blend Composition and Yarn Evenness (CVm%)

The coefficient of mass variation (CVm%) across the seven experimental runs ranged from 14.74% to 16.93%. As shown in

Fig. 2a, run 3 exhibited the lowest CVm% (14.74%), corresponding to a blend of 20% recycled cotton, 50% eco-viscose,

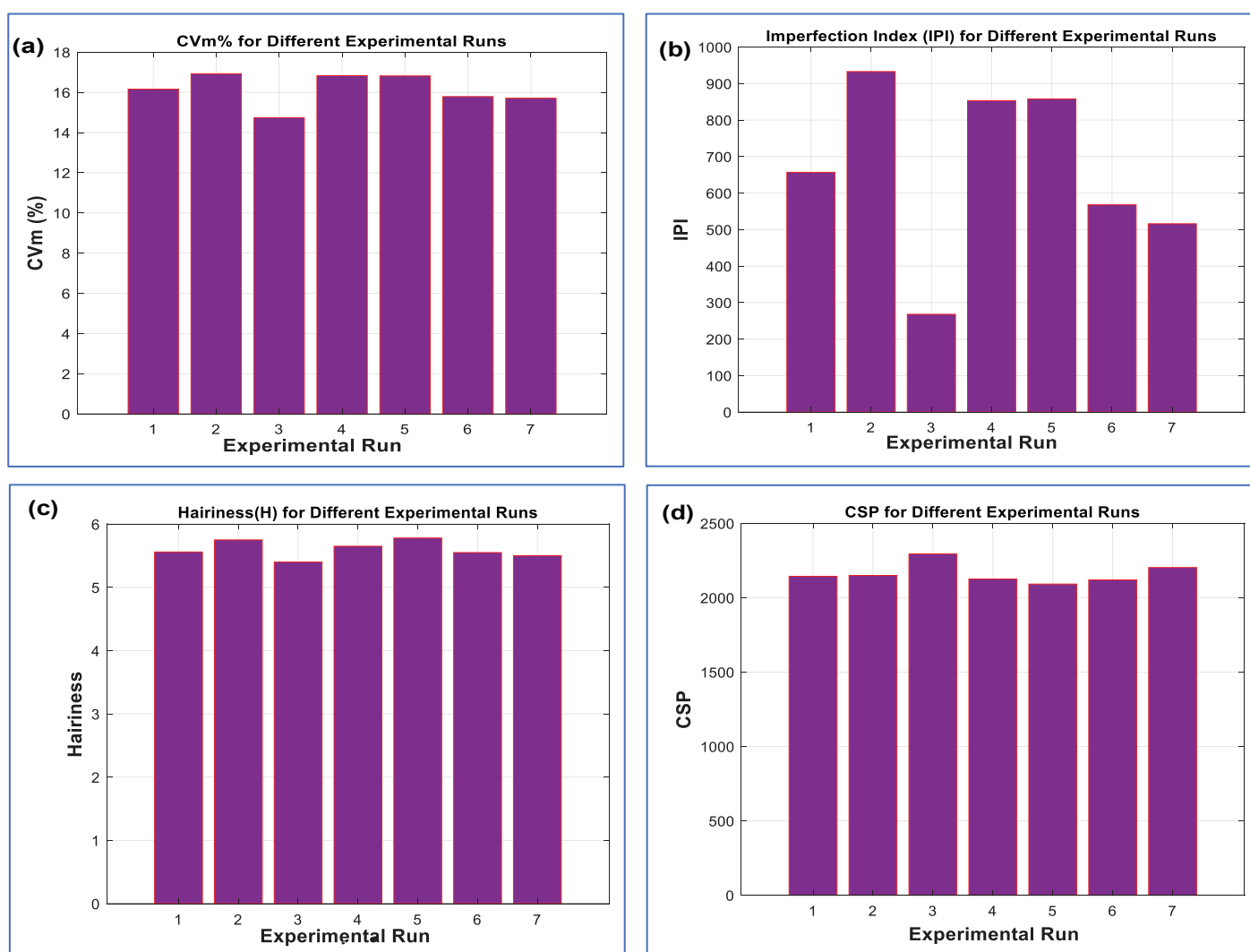


Figure 2: Variation of yarn properties across experimental runs: (a) CVm%, (b) IPI, (c) Hairiness, and (d) CSP for different recycled cotton, eco-viscose, and modal blend compositions.

and 30% modal. The high eco-viscose content likely improved fibre uniformity and drafting stability, resulting in better yarn evenness. The improvement in yarn evenness with higher eco-viscose and modal content can also be explained by fibre migration behavior within the yarn structure. Regenerated fibres with more uniform length and fineness tend to migrate more regularly between the yarn core and surface during twisting. This controlled migration improves fibre cohesion and reduces local mass variation. In contrast, recycled cotton fibres with higher short fibre content (Table 1) exhibit irregular migration, which increases yarn unevenness.

In contrast, run 2, which contained the highest recycled cotton proportion (30%), showed the highest CVm% (16.93%). Recycled cotton fibres are generally shorter and more variable in fineness, leading to increased drafting irregularity. The trend observed in Fig. 2a confirms that yarn evenness decreases with higher recycled cotton levels, while a dominant eco-viscose proportion mitigates irregularity.

3.3 Fibre Blend Composition and Imperfection Index (IPI)

The Imperfection Index (IPI) varied significantly across the blends, ranging from 268 to 933 (Fig. 2b). The maximum IPI value in Run 2 (933) highlights the detrimental effect of higher recycled fibre content on yarn cleanliness. Short fibre length, nep formation, and fibre variability inherent in recycled cotton contribute to higher counts of thin places, thick places, and neps. The increase in imperfection index with higher recycled cotton content can also be related to drafting wave mechanics during spinning. Fibres with shorter lengths and higher variability tend to move irregularly in the drafting zone, producing unstable fibre flow known as drafting waves. These drafting waves lead to the formation of thin places and thick places in the yarn. The relatively longer and more uniform eco-viscose and modal fibres (Table 1) improve drafting stability and reduce imperfection generation. Run 3, with 50% eco-viscose, exhibited the lowest IPI (268), indicating superior drafting performance and lower imperfection generation. The stabilising influence of eco-viscose is clearly visible in Fig. 2b,

where runs with higher eco-viscose content consistently show lower imperfection levels. Runs 4 and 5 (IPI ~ 853–858) demonstrate that even moderate changes in blend ratios of viscose and modal can affect yarn regularity.

Overall, the results show that IPI is highly sensitive to recycled cotton content, and eco-viscose significantly improves yarn quality by reducing imperfections.

3.4 Fibre Blend Composition and Hairiness Index

Table 8: Neps analysis at different processing stages

Processing Stage	Parameter	Run -1	Run -2	Run -3	Run -4	Run -5	Run -6	Run -7
Mixing	Fiber neps (FN)/g	207	276	192	231	176	205	178
	FN size (μm)	694	698	676	692	692	685	685
	Seed -coat neps (SCN)/g	30	36	28	35	28	32	31
	SCN size (μm)	1307	1336	1317	1339	1309	1310	1315
Card Sliver	Fiber neps (FN)/g	33	19	23	18	24	22	16
	FN size (μm)	545	528	551	531	542	541	531
	Seed -coat neps (SCN)/g	6	4	4	5	5	3	4
	SCN size (μm)	762	768	771	730	762	780	746
Finisher Drawn Sliver	Fiber neps (FN)/g	21	19	13	20	20	22	12
	FN size (μm)	547	542	545	554	552	556	528
	Seed -coat neps (SCN)/g	3	3	2	3	3	3	3
	SCN size (μm)	754	772	783	787	767	761	753

Although differences are subtle, Fig. 2c demonstrates that fibre composition influences hairiness, but hairiness is the least affected property compared to CVm% and IPI. The variation in yarn hairiness can also be interpreted in relation to the AFIS neps analysis results presented in Table 8. The nep measurements indicate that recycled cotton-rich blends exhibited relatively higher fibre nep counts at the mixing stage. Although carding and draw-frame processes significantly reduced nep levels, some small fibre clusters and short fibres remained in the finisher drawn sliver. These residual neps and short fibres tend to migrate toward the yarn surface during spinning and contribute to protruding fibre ends, resulting in increased yarn hairiness. Blends containing higher eco-viscose and modal proportions showed comparatively lower nep levels after processing, which contributed to more uniform fibre alignment and slightly reduced hairiness values.

3.5 Fibre Blend Composition and Count Strength Product (CSP)

The CSP values ranged between 2092 and 2295, as shown in Fig. 2d. The highest CSP (2295) was observed in Run 3, mirror-

The hairiness index remained relatively stable across all runs, varying between 5.40 and 5.78, as illustrated in Fig. 2c. Run 3 maintained the lowest hairiness (5.40), likely due to the smoother, longer and more uniform eco-viscose and modal fibres that help in fibre alignment and reduce protruding fibre ends. Run 5 displayed the highest hairiness (5.78). This slight increase may be attributed to higher recycled content and fibre length irregularity, leading to more fibre ends protruding from the yarn body.

ing the favourable trends in evenness, IPI, and hairiness. The combination of 50% eco-viscose and 30% modal likely increase fibre cohesion and tensile performance, thereby enhancing yarn strength. Another important factor influencing yarn strength is fibre packing density. Eco-viscose and modal fibres have finer and more uniform diameters compared to recycled cotton (Table 1), allowing better packing within the yarn cross-section. Higher packing density increases inter-fibre friction and load-sharing efficiency, which contributes to improved yarn strength. In contrast, the higher short fibre content of recycled cotton reduces packing efficiency and weakens fibre cohesion. The lowest CSP (2092) occurred in Run 5, which also had the highest hairiness. Increased fibre protrusion can weaken fibre bonding within the yarn structure, resulting in reduced strength. Runs 1, 2, 4, and 7 showed moderate CSP values (2144–2203), reflecting the influence of different viscose-modal proportions on yarn strength. Fig. 2d confirms that CSP improves significantly with higher eco-viscose content and decreases as recycled fibre proportion increases beyond the optimum level.

3.6 Response Surface Analysis of Fiber Blend Composition

Three-dimensional response surface plots were developed to visualize the influence of recycled cotton, eco-viscose, and modal fibre proportions on yarn properties, as shown in Figure 3. The fibre blend composition is represented along the three axes, while the corresponding yarn response values are illustrated using color gradients.

The surface plot for CVm% shows that yarn evenness improves as the proportion of eco-viscose and modal increases and recycled cotton decreases. Higher recycled cotton content tends to increase mass irregularity due to the presence of shorter and less uniform fibres. The lowest CVm values are observed in blends containing approximately 20–23% recycled cotton combined with higher eco-viscose content.

The response surface for IPI demonstrates a similar trend, where imperfection levels decrease with increasing eco-viscose proportion and lower recycled cotton content. This behaviour indicates that regenerated fibres contribute to improved drafting stability and reduced nep formation. Blends with higher recycled cotton levels exhibit noticeably higher IPI values.

hairiness is less sensitive to blend composition compared to CVm and IPI. Slightly lower hairiness values are observed in blends with higher eco-viscose and modal content, which can be attributed to improved fibre alignment and smoother fibre surfaces.

The response surface for CSP shows an opposite trend compared to CVm and IPI, where yarn strength increases with higher eco-viscose and modal proportions. The highest CSP values are observed in blends containing lower recycled cotton content, indicating improved fibre cohesion and tensile performance. Increasing recycled cotton beyond approximately 25–30% leads to a noticeable reduction in yarn strength. The results also indicate a synergistic interaction between modal and eco-viscose fibres. Eco-viscose contributes to yarn uniformity due to its consistent fibre length and fineness, while modal provides higher tensile strength because of its superior tenacity (Table 1). The combined presence of these regenerated fibres improves fibre alignment and load distribution, resulting in enhanced yarn quality compared with blends dominated by recycled cotton. The yarn quality values obtained in this study are comparable with previously reported results for regenerated fibre blends. Earlier studies on cotton–modal and cotton–viscose blended yarns reported CVm values typically ranging between 14–18% and CSP values between 2100–2300 for similar yarn counts [13]. The results obtained in the present study fall within these ranges, confirming that recycled cotton blended with eco-viscose and modal fibres can produce yarns with comparable quality to conventional regenerated fibre blends.

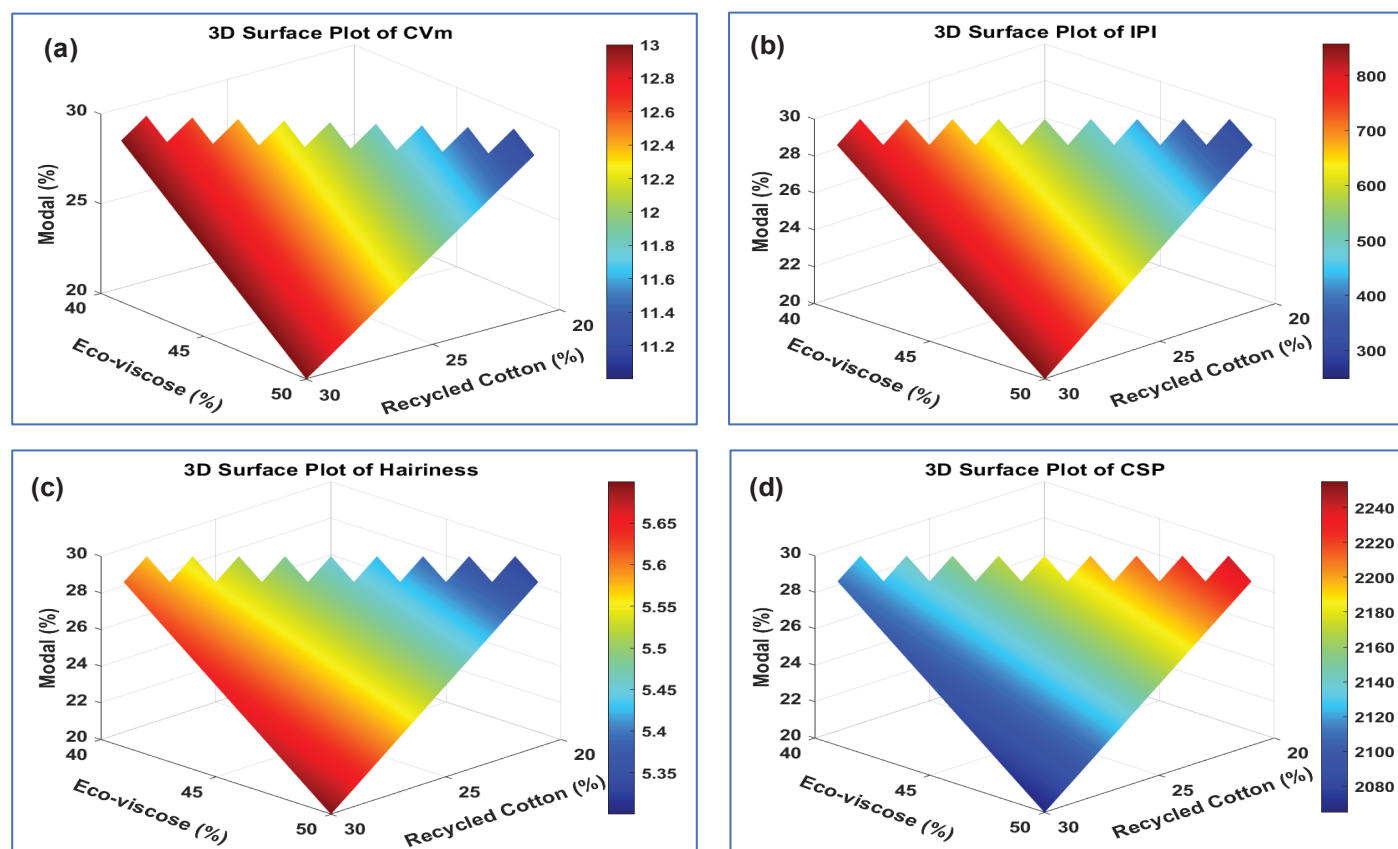


Figure 3: Three-dimensional response surface plots showing the effect of recycled cotton, eco-viscose, and modal blend composition on yarn properties: (a) CVm%, (b) IPI, (c) Hairiness, and (d) CSP. Yarn responses are represented by color gradients.

3.7 Optimization of Fiber Blend Composition

Optimization of the fibre blend composition was carried out using a desirability-based multi-response optimization approach. The objective was to obtain maximum CSP and minimum CVm%, IPI, and hairiness, since these parameters collectively determine yarn quality and performance. The optimization criteria and response goals are presented in Table 8. CSP was set to be maximized within the experimental range, while CVm%, IPI, and hairiness were minimized. Equal weights and importance levels were assigned to all responses to ensure balanced optimization.

Table 9: Optimization Criteria for Multi-response Desirability Analysis

Response	Goal	Lower	Target	Upper	Weight	Importance
(CSP)	Maximum	2092	2295.00		1	1
(Hairiness)	Minimum		5.40	5.78	1	1
(IPI)	Minimum		268.00	933.00	1	1
(CVm%)	Minimum		14.74	16.93	1	1

Table 10: Optimal Fiber Blend Composition and Predicted Yarn Properties

Solution	(Rec. Cotton)	(Eco - viscose)	(Modal)	(CVm%) Pred.	(IPI) Pred.	(Hairiness) Pred.	(CSP) Pred.	Composite Desirability
1	20	50	30	14.7822	288.407	5.4237	2275.12	0.974561

The multi-response optimization results obtained using the desirability function approach are illustrated in Figure 4. The optimization aimed to minimize CVm%, IPI, and hairiness while maximizing CSP within the selected blend range. The optimum fibre blend composition was identified at 20% recycled cotton, 50% eco-viscose, and 30% modal, corresponding to a composite desirability value of 0.9746, which indicates excellent agreement with the optimization objectives.

3.8 Validation of Optimization Results

To verify the accuracy of the developed regression models, the predicted yarn properties at the optimum blend composition were compared with the experimentally measured values. The predicted values showed good agreement with the experimental results. The small prediction errors confirm that the developed regression models provide reliable estimates of yarn properties within the studied blend region. The high composite desirability value (0.9746) further indicates that the selected blend composition provides an excellent balance between yarn evenness, imperfections, hairiness, and strength. These results demonstrate the effectiveness of the desirability-based optimization approach for designing sustainable tri-blend yarns.

The optimal fibre blend composition obtained from the desirability function analysis is presented in Table 10. The optimum solution corresponds to a blend containing 20% recycled cotton, 50% eco-viscose, and 30% modal, with a composite desirability value of 0.9746, indicating excellent agreement with the optimization objectives.

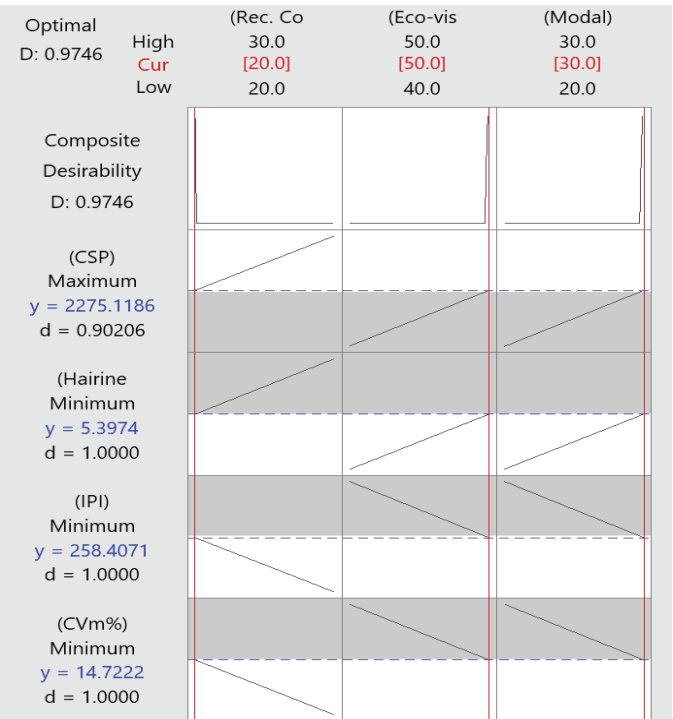


Figure 4: Multi-response desirability optimization plot showing the effect of recycled cotton, eco-viscose, and modal proportions on yarn properties and the optimal blend composition (D = 0.9746).

Table 11: Comparison of Predicted and Experimental Values at Optimum Blend Ratio

Property	Predicted	Experimental	Error (%)
CVm (%)	14.78	14.51	1.86
IPI	288.41	296	2.56
Hairiness	5.424	5.43	0.11
CSP	2275.12	2303	1.21

Table 12: Manufacturing Cost of 1 kg of 30 Ne Cotton/Regular Viscose/Modal and Recycled Cotton/Eco-Viscose/Modal Tri-blend Yarn Based on Optimized Blend Proportions

Cost Components	Price (USD/kg)	20% Cotton + 50% Viscose + 30% Modal	20% recycled cotton + 50% eco- viscose + 30% modal
Virgin cotton (Cameroon) (a)	2.25	0.45	–
Regular Viscose (b)	1.80	0.90	–
Modal (c)	2.70	0.81	0.81
Recycled Cotton (d)	1.12	–	0.224
Eco-Viscose (e)	1.68	–	0.84
Total raw materials (f)	–	2.16	1.87
Processing waste (g)	–	12%	15%
Raw material cost considering waste (h) = f/(1–g)	–	2.45	2.20
Waste price (i)	0.80	0.80	0.80
Net Raw Material Cost (j) = (h – i)	–	1.65	1.40
Manufacturing overhead (k)	–	1.50	1.55
Total Yarn Cost (j+k)	–	3.15 USD/kg	2.95 USD/kg

3.9 Economic Analysis of Optimized Tri-blend Yarn Production

Table 12 presents the manufacturing cost comparison between conventional cotton/viscose/modal yarn and the proposed recycled cotton/eco-viscose/modal tri-blend yarn based on the optimized blend composition. The results indicate that the sustainable tri-blend yarn reduces production cost by approximately 6% compared to the conventional blend. The lower cost is mainly attributed to the reduced price of recycled cotton and eco-viscose fibres. Although higher processing waste and slightly increased manufacturing overhead were observed for recycled fibre processing, the overall yarn production cost remained economically advantageous.

4. Conclusion

This study evaluated blend ratios of recycled cotton, eco-viscose, and modal fibre has a great influence on yarn quality parameters. 20% recycled cotton in blend proportion produced the best quality yarn. This blend showed the lowest CVm%, lowest IPI, lowest hairiness, and highest CSP. The findings clearly indicate that eco-viscose acts as an effective stabilizing fibre, improving yarn evenness, reducing imperfections, and enhancing strength particularly when combined with modal. when recycled cotton is increased to around 25–30%, the yarn quality starts to drop. A noticeable deterioration in evenness and imperfection levels arises due to higher short-fibre content. The application of the mixture design approach proved effective.

tive in systematically evaluating the influence of fibre blend composition and identifying the optimum blend ratio with a reduced number of experimental trials. The developed regression models and desirability optimization provided reliable prediction of yarn properties within the studied blend range. Overall, the study confirms that recycled cotton can be adopting up to approximately 20–25% without compromising yarn quality and performance. This balance ensures both sustainability and acceptable yarn quality. The outcomes offer practical guidance for developing environmentally sustainable yarns with competitive yarn quality and performance in textile applications.

Author Contribution Statement

Mohammad Rashel Hawlater: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ahmed Jalal Uddin: Conceived and designed the experiments; Performed the experiments; Contributed in analysis tools or data; Supervise the work; Wrote and revise the paper.

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Declaration of Conflicting Interest

The authors declare no conflict of interest.

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