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Toward Circular Economy-Driven Sustainable Yarn Blends: Statistical Modeling and Multi-Response Optimization

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Article

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ABSTRACT

Textile industries are increasingly shifting toward eco-friendly fibers in response to environmental concerns, regulatory pressures, rising raw material costs, and growing consumer demand for sustainable apparel. In this context, a sustainable tri-blend yarn was developed using eco-viscose, recycled cotton, and modal fibers. The eco-viscose comprised a 30/70 blend of Circulose and Ecovero pulps, where Circulose is derived from post-consumer cotton textile waste and Ecovero originates from sustainably managed wood sources. Recycled cotton was incorporated as a partial substitute for virgin cotton, while a substantial proportion of modal fiber was included to enhance the mechanical performance required for fabric production. An extreme vertices mixture design combined with response surface methodology was employed to optimize the blend proportions. The design generated fourteen experimental runs, including replicates. Yarn quality parameters were evaluated, and regression models were developed to describe the responses. The optimization targeted minimization of unevenness, imperfection index, and hairiness, alongside maximization of count strength product (CSP), tenacity, and elongation. The optimal blend composition was obtained as 40.0% eco-viscose, 20.3% recycled cotton, and 39.7% modal. Experimental validation showed good agreement with predicted values, with deviations ranging from 0.23% to 4.97%, confirming the adequacy and reliability of the developed models.

KEYWORDS

eco-viscose, circulose, ecovero, sustainable yarn, recycled cotton, mixture design

INTRODUCTION

The “fast fashion” business strategy was embraced by major international clothing stores in the 1990s in order to manufacture vast quantities of inexpensive, trendy clothing that reacts swiftly to shift in customer demand [1-3]. Fast fashion allows customers to buy trendy garments at low prices, but it is essentially unsustainable,

as it speeds up fiber utilization and clothing disposal and presents a significant environmental challenge [4-7]. This includes significant environmental burdens on water consumption, pollution, microplastics, toxic chemicals, and carbon emissions [8-10]. Disposable fashion produces around 92 million tons of textile trash every year, and this number is projected to be around 134 million tons by the year 2030 [11]. In addition, the sector accounts for 20% of global wastewater discharge and 10% of global carbon emissions [12]. This has made the sector more integrated with Sustainable Development Goal (SDG) 12 for responsible consumption and production, through sound chemical management and waste reduction through recycling and reuse [13-14]. Cotton is the second most widely produced fiber globally, after polyester, and nearly 75% of clothing contains some portion of cotton [15]. On the contrary, cotton production is very water-intensive, consuming around 198 Gm^3 of water globally every year [16], and producing 1 kg of cotton fiber requires 10,000-20,000 L of water [17]. The production of cotton is also reliant on a great deal of pesticides and fertilizers that are harmful to the environment and human health, whilst the dyeing and finishing of cotton products adds to the wastewater pollution. Consequently, there is a rising focus on decreasing the dependence on virgin cotton by utilizing sustainable alternatives, especially the recycled cotton fibers sourced from textile waste, which require less environmental load and lessen the consumption of newly grown cotton [18-19].

Viscose fiber, primarily derived from wood pulp, is valued for its silky luster, softness, moisture absorbency, and drape but exhibits relatively low strength, especially in wet conditions [20]. Conventional viscose production contributes to deforestation and depends on hazardous chemicals that pose environmental and occupational health risks. Carbon disulfide exposure can adversely affect workers' reproductive health and nervous systems, while sodium hydroxide causes severe corrosion [21]. In addition, large volumes of wastewater are generated during viscose production, and insufficient treatment often leads to polluted effluents being discharged into waterways [22-23].

To address these concerns, Renewcell developed a process to convert cellulosic textile waste into a biodegradable pulp known as Circulose [24]. Circulose pulp may be used to produce regenerated fibers, including viscose, lyocell, or modal, and has mostly been employed in viscose manufacturing without the usage of toxic chemicals [25]. Textiles derived from circulose allow the production of high-quality clothes composed completely of recycled materials. The pulp is abundant in cellulose, predominantly derived from cotton, with its cellulose concentration rising from 90-95% to nearly 99% following scouring and bleaching processes

that eliminate impurities [26-27], enhancing desirable fiber characteristics such as strength, durability, and absorbency.

Eco-viscose, marketed as Ecovero, is a sustainable viscose fiber created by the Austrian firm Lenzing, derived from certified renewable wood sources. The raw materials are sourced from sustainably managed forests certified by entities such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). These certifications ensure that the raw materials are obtained responsibly without causing deforestation or ecological degradation. In contrast to traditional viscose, the manufacture of eco-viscose necessitates considerably reduced water and energy use while producing less emissions [28].

Modal fiber, which comes largely from beech tree pulp, is known for being stronger and more elastic than other types of fiber. Compared to cotton, it absorbs more, lasts longer, dries faster, and is less likely to pill, making it good for things like underwear and sports [29]. Modal stays strong in wet places and doesn't shrink much after washing [30]. Modal is frequently thought to be better for the environment than cotton since beech trees grow quickly, use less water, and help absorb CO_2 from the air [31].

In addition to selecting sustainable fiber resources, optimizing the processing parameters and blend composition is essential to ensure that recycled and regenerated fibers can meet industrial yarn quality requirements. In textile manufacturing, the interactions among multiple variables such as fiber properties, blend ratios, and spinning conditions often influence the final yarn characteristics in a complex and nonlinear manner [32]. To address such complexity, statistical design and optimization techniques have been increasingly adopted to systematically evaluate the relationships between process variables and product responses while minimizing experimental effort [33]. Methods such as Central Composite Design (CCD), Response Surface Methodology (RSM), artificial neural networks (ANN), machine learning models, and hybrid statistical-computational frameworks have been widely applied for process optimization in various material and chemical systems [34-37]. These modern statistical approaches enable efficient parameter selection, process optimization, and performance prediction, thereby supporting the development of sustainable materials and industrial processes [38]. Recent research has investigated sustainable tri-blend yarns based on recycled cotton, recycled polyester, and regenerated fibers, where statistical and AI-based modeling methods have been applied to optimize yarn performance and blend composition [39-40]. Unlike many previous studies that incorporate recycled cotton only at limited levels with the virgin cotton [41], the present work demonstrates the complete replacement of virgin cotton with recycled cotton in producing ring-spun yarns through an optimized combination of

recycled cotton, eco-viscose, and modal fibers. The novelty of this study lies not only in the statistical techniques themselves, but in their industrial-scale application using quadratic mixture regression modeling, response surface methodology (RSM), and desirability-based multi-response optimization to optimize a newly developed eco-viscose system composed of Circulose and Ecovero pulp in combination with recycled cotton under strict spinnability and fabric-manufacturing constraints. Integrated assessment approaches considering mechanical performance, economic feasibility, and environmental impact are increasingly used to evaluate the sustainability of new material systems [42]. By integrating quadratic mixture modeling with experimental validation at yarn, this study provides a scalable and industry-relevant framework for maximizing recycled fiber utilization while maintaining yarn performance, processability, and cost efficiency.

MATERIALS AND METHODS

Raw Materials

Recycled cotton fibers (purple in color), obtained by shredding purple pre-consumer knit garment clips, were sourced from Akij Recycled Plant, Dhaka, Bangladesh. The use of purple recycled fibers was deliberately chosen to impart a distinctive mélange shade to the yarn, in contrast to the predominantly grey mélange yarns commonly available in the market. However, the recycled fibers were produced through an industrial mechanical shredding process involving multi-stage opening and fiberization, where a sequence of tearing and opening rollers progressively disintegrated the fabric into individual fibers. Owing to the aggressive nature of this process, some reduction in fiber length, increased short fiber content, and partial loss of fiber strength are unavoidable.

Fiber quality was assessed using High Volume Instrument (HVI), and the corresponding results are presented in Table 1.

Eco-viscose (made from a 30/70 blend of Circulose and Ecovero pulp) and Modal fiber, both originating from China, were collected through local suppliers. Figs. 1 (a-c) shows the three fiber types employed in this study, along with their microscopic images. The properties of these fibers, determined using a High-Volume Instrument (HVI) according to ASTM D5867-05 [43] and supported by information from supplier documentation, are summarized in Table 1.

Table 1. Properties of fibres used

Parameters	Recycled cotton	Eco-viscose	Modal
Length or Upper Half Mean Length (UHML) (mm)	24.30 ± 0.40	38.00	38.00
Uniformity Index	63.51 ± 1.04	-	-
Fineness (dtex)	1.77 ± 0.01	1.33	1.30
Short fiber content (SFC)% (< 12.7 mm)	41.80 ± 1.90	-	-
Tenacity (cN/tex)	18.51± 0.88	23.40	36.00
Elongation (%)	7.01± 0.12	17.30	14.00
Moisture regains (%)	8.50 ± 0.03	11.51	11.20

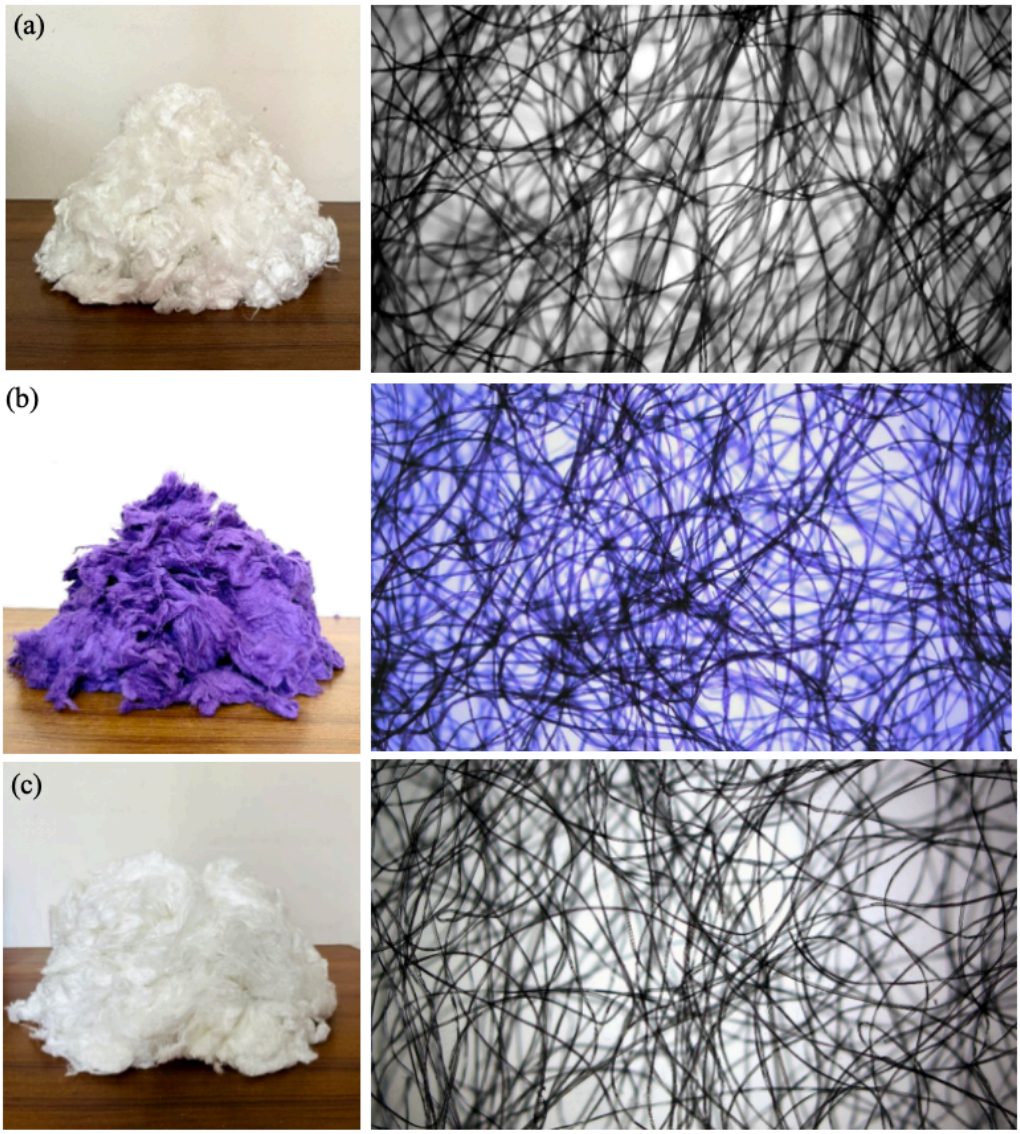


Figure 1. (a) Eco-viscose (b) Recycled cotton, and (c) Modal fiber and their respective microscopic images (50×).

Experimental design and optimization process

A quadratic mixture design combined with response surface methodology (RSM) was employed to determine the optimal proportions of recycled cotton, eco-viscose, and modal fibres for producing sustainable tri-blend yarns with balanced quality and performance. Statistical analyses such as regression, analysis of variance (ANOVA), and desirability-based multi-response optimization were performed in Minitab statistical software (Version 2022).

The responses recorded in mixture experiments mainly depend on the proportions of the components and not on absolute amounts, subject to the constraint that the sum of all components equals unity. Accordingly, recycled cotton (X1), eco-viscose (X2), and modal (X3) were treated as mixture variables satisfying the condition X1 + X2 + X3 = 100%.

Based on industrial spinning practice and supporting literature, lower and upper bounds were imposed on each component to ensure spinnability and acceptable yarn quality. The selected bounds were defined based on practical spinnability limits observed in industrial processing, where higher proportions of recycled cotton (>30%) tend to result in excessive yarn irregularity, increased breakage, and unstable spinning due to the high short-fiber content and reduced fiber cohesion [41]. Conversely, reducing recycled cotton below 20% would limit the sustainability objective of incorporating a meaningful proportion of recycled material. Therefore, the chosen range represents a balanced and practically achievable domain that ensures process stability while maintaining significant recycled fiber utilization. The adopted constraint-based design focuses on identifying an optimal composition within this feasible region rather than exploring unrealistic or non-spinnable blend ratios. Eco-viscose was constrained within the range of 40-60% to enhance softness and moisture absorbency, while modal was maintained between 20-40% to compensate for strength loss and to improve elongation. These limits defined the feasible experimental region for the mixture design.

The experimental design was generated using an Extreme Vertices mixture design, resulting in 14 experimental runs consisting of 9 distinct design points and 5 replicated runs, which were included to estimate experimental error and verify the reproducibility of the measured yarn properties. Table 2 displays the proportions of recycled cotton, eco-viscose, and modal for each trial run.

Table 2. Proportion of mixture component for experimental runs

Run	Blend ratio		
	X1% (r-Cotton)	X2% (Eco-viscose)	X3% (Modal)
1	22.5	53.75	23.75
2	20	40	40
3	20	60	20
4	30	40	30
5	22.5	43.75	33.75
6	25	47.5	27.5
7	30	40	30
8	25	47.5	27.5
9	20	60	20
10	20	40	40
11	27.5	43.75	28.75
12	30	50	20
13	27.5	48.75	23.75
14	30	50	20

· Blend constraints: $20 \leq X1 \leq 30\%$, $40 \leq X2 \leq 60\%$, $20 \leq X3 \leq 40\%$

· Mixture constraint: $X1 + X2 + X3 = 100\%$

· Replicate runs (run number 7, 8, 9, 10 and 14) were included to evaluate experimental variability and model robustness.

Six yarn quality parameters were considered as response variables in the experimental design. The coefficient of mass variation (CVm%) was defined as Y1, imperfection index (IPI) as Y2, hairiness as Y3, count strength product (CSP) as Y4, tenacity (cN/tex) as Y5, and elongation (%) as Y6. Mixture design also determined the number of experimental runs (fourteen in this case) and specified the proportion of each fiber component, such as X1 % (recycled fiber), X2% (eco-viscose), and X3% (modal), for each run, as presented in Table 2. The experimental data were fitted to quadratic mixture regression models to account for both individual component effects and binary interaction effects among the fibres.

Model adequacy was evaluated using standard statistical indicators, including the coefficient of determination (R^2), adjusted R^2, predicted R^2, and predicted residual sum of squares (PRESS). The validated models were subsequently employed in a desirability-function-based multi-response optimization framework to simultaneously minimize yarn irregularity and surface defects while maximizing mechanical performance. The overall experimental workflow adopted in this study is schematically illustrated in Fig. 2.

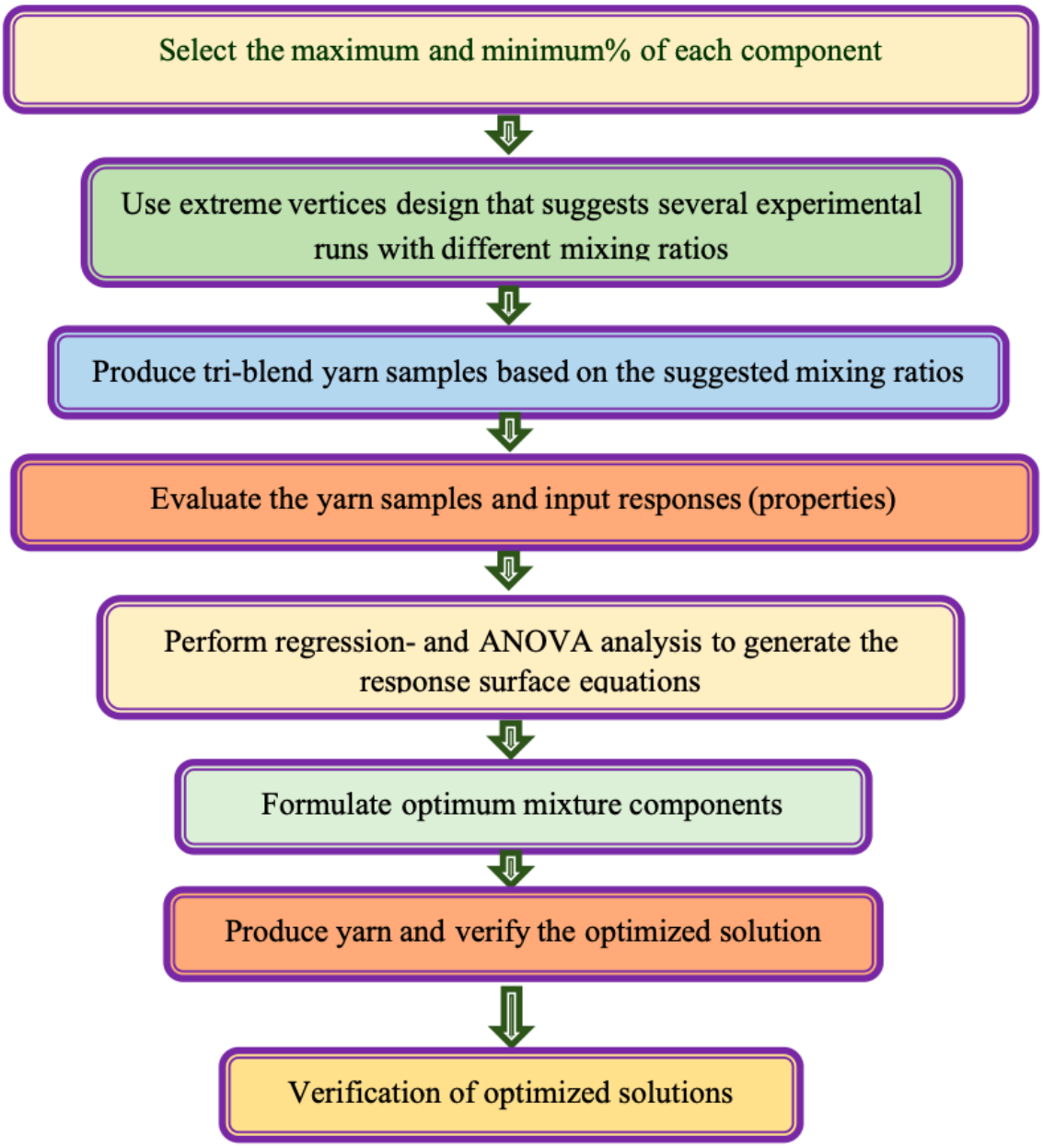


Figure 2. Schematic representation of the experimental design and mixture-based optimization procedure.

Preparation of Yarn Samples

Accurately weighed amounts of recycled cotton, eco-viscose, and modal fibers were blended according to the experimental runs in Table 2 to prepare an approximately 25 kg fiber mixture. This quantity ensured the production of at least 10 rovings (>1 kg each), providing sufficient material for yarn testing and fabric sample preparation. The fibers were thoroughly hand-mixed and conditioned at ambient temperature for a minimum of eight hours prior to processing.

The blended fibers were processed through the blow room and fed into the carding machine via chute feed. The carded slivers were then equalized in two stages: first in the breaker draw frame (6-doubling) and subsequently in the finisher draw frame (8-doubling). Fiber blending was initiated through manual mixing and progressively enhanced during blow room, carding, and draw-frame processing. A homogeneous fiber blend was ultimately achieved at the finisher draw frame, as evidenced by the sliver images in Fig. 3.



Figure 3. Delivery slivers obtained from (a) the carding machine, (b) breaker draw frame, and (c) finisher draw frame.

The finisher-drawn slivers were processed on the Simplex machine to produce rovings, which were subsequently fed into the creels of the ring-spinning frame to spin 30 Ne (19.68 Tex) yarns. Detailed technical specifications of the yarn production process are listed in Table 3. Following this procedure fourteen sets of yarn samples corresponding to the different blend ratios from the fourteen experimental runs (outlined in Table 2) were successfully manufactured.

Experimental instruments, testing conditions, and standards

The instruments and relevant standards employed for fibre and yarn characterization in this study are summarized in Table 4. Before testing, the specimens were conditioned at a standard testing atmosphere of 65 ± 2% relative humidity and 27 ± 2 °C, representative of tropical conditions, in accordance with ASTM D1776/D1776M-15 [44]. For each experimental run, ten bobbin samples were tested, and the reported yarn properties represent the mean values of these ten measurements.

Table 3. Production parameters for producing tri-blend yarn

Processing stage	Equipment (manufacturer & model)	Country of origin	Output material & linear density	Operating conditions
Bale opening & blow room	Trützschler BO-E 1200 with TO-T1 chute feed	Germany	Card mat, 650 ktex	Throughput ≈ 1000 kg·h^{-1}

Processing stage	Equipment (manufacturer & model)	Country of origin	Output material & linear density	Operating conditions
Carding	Trützschler T19i card	Germany	Card sliver, 6.38 ktex	Production rate ≈ 50 kg·h^{-1}
Breaker drawing	Rieter SB-D 50 draw frame	Switzerland	Drawn sliver, 5.88 ktex	Delivery speed 600 m·min^{-1}, 6 doublings
Finisher drawing	Rieter RSB-D 50 draw frame	Switzerland	Drawn sliver, 5.30 ktex	Delivery speed 600 m·min^{-1}, 8 doublings
Roving (simplex)	HongYuan HY492E	China	Roving, 0.79 ktex (TPI 0.85)	Flyer speed ≈ 900 rpm
Ring spinning	Jingwei F1508	China	Yarn count 30 Ne (19.68 tex), TPI 20.40	Spindle speed ≈ 16,000 rpm

Table 4. Instruments, testing conditions, and standards used for fibre and yarn characterization

Property / Analysis	Instrument / Equipment	Manufacturer & Model	Test conditions	Standard
Fibre characterization	High Volume Instrument (HVI) and	Uster Technologies	Standard laboratory conditions	ASTM D5867-05
	Advanced Fiber Information System (AFIS Pro-2)	Uster Technologies	Standard laboratory conditions	ASTM D5866-05
Yarn mass variation (CVm%)	Uster® Tester 6 (UT 6)	Uster Technologies, Switzerland	Mass variation at 8 mm cut length	ASTM D1776/ D1776M-15
Imperfection Index (IPI)	Uster® Tester 6 (UT 6)	Uster Technologies, Switzerland	Thick (+50%), thin (−50%), neps (+200%) per 1000 m	
Yarn hairiness (H)	Uster® Tester 6 (UT 6)	Uster Technologies, Switzerland	Optical (photoelectric) detection of protruding fibres within 1 cm	ISO 16549
Tensile properties (Tenacity, Elongation)	Tenso-Lab 4 Tensile Strength Tester	Mesdan Lab, Italy	Gauge length 500 mm; speed 500 mm/min; pretension 5 cN; load cell 100 N; 10 tests/sample	EN ISO 2062:2009
Surface morphology	Optical microscope; Scanning electron microscope (SEM)	Carl Zeiss Axiolab 5 (Germany); JEOL JSM-6460LV (Japan)	Morphological observation	—

RESULTS AND DISCUSSION

Yarn appearance and response data

Using the blend ratios specified for the fourteen experimental runs from the mixture design, fourteen sets of 30 Ne (19.68 Tex) yarns were spun on the ring frame. Representative yarn packages from each run are shown in Fig. 4.

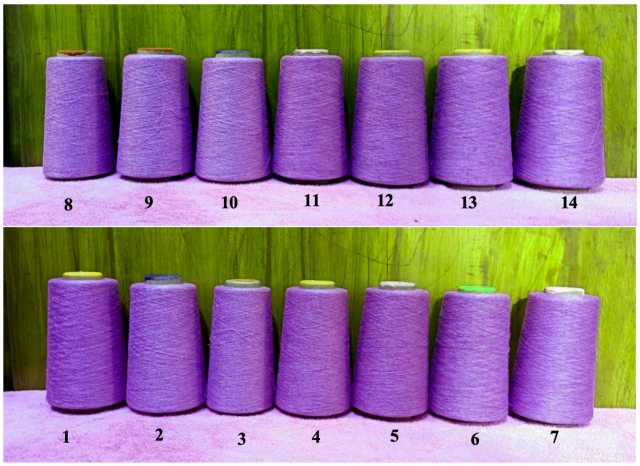


Figure 4. Yarn packages produced from fourteen experimental blend compositions of recycled cotton, eco-viscose, and modal.

All yarns exhibited a mélange appearance with slight shade variations, reflecting the differing amounts of purple recycled cotton used (ranging from 20% to 30%, as indicated in Table 2). Incorporating a broader spectrum of colored recycled fibers could have produced more pronounced differences in the mélange effect. Nevertheless, each yarn was subjected to laboratory testing, and the measured values for CVm% (Y1), IPI (Y2), hairiness (Y3), CSP (Y4), tenacity (Y5), and elongation (Y6) were documented in the design matrix, as presented in Table 5.

Table 5. Experimental data of fourteen yarn samples

Run	Factors			Responses (Yarn properties)					
	X1% r-Cotton	X2% Eco-Viscose	X3% Modal	Y1 CVm%	Y2 IPI(counts/km)	Y3 Hairiness	Y4 CSP	Y5 Tenacity(cN/Tex)	Y6 Elongation (%)
1	22.50	53.75	23.75	15.88	590	5.56	2185	14.15	8.02
2	20	40	40	15.42	485	5.48	2248	14.78	8.64
3	20	60	20	15.35	455	5.47	2235	14.62	8.36
4	30	40	30	16.97	937	5.75	2150	13.22	8.09
5	22.50	43.75	33.75	15.64	540	5.52	2218	14.42	8.49
6	25	47.50	27.50	15.71	516	5.50	2203	14.09	8.45
7	30	40	30	16.89	905	5.72	2166	13.31	8.13
8	25	47.50	27.50	15.79	568	5.55	2120	14.20	7.94
9	20	60	20	15.29	440	5.45	2242	14.7	8.43
10	20	40	40	15.48	505	5.49	2260	14.85	8.73
11	27.50	43.75	28.75	16.16	657	5.56	2144	13.83	7.82
12	30	50	20	16.65	820	5.71	2110	13.40	7.76
13	27.50	48.75	23.75	16.83	851	5.65	2126	14.39	7.63
14	30	50	20	16.87	853	5.78	2092	12.99	7.51

Model adequacy statistics for quadratic mixture regression models

Table 6 summarizes the goodness-of-fit and predictive performance of the quadratic mixture regression models developed for all yarn quality responses. The standard error of regression (S), coefficient of determination (R^2), adjusted R^2, predicted R^2, and predicted residual sum of squares (PRESS) were used to evaluate model adequacy and predictive reliability.

The R^2 values for all replies are above 85%, which means that the composition of the fiber mix explains a large part of the differences in yarn qualities. Tenacity (R^2 = 93.94%) and hairiness (R^2 = 93.29%) had the most explanatory power, which means that these reactions are quite sensitive to the quantities of the blends. The adjusted R^2 values are quite similar to the R^2 values, which shows that adding quadratic mixing factors did not cause the model to overfit.

The predicted R^2 values show how well the models can be used in other situations. CSP (81.56%), tenacity (81.08%), and hairiness (79.78%) were the most accurate predictors, showing that the mixture models can consistently estimate these qualities in the experimental domain. On the other hand, elongation (66.63%), IPI (71.96%), and CVm% (74.29%) had lower predicted R^2 values, which means that the experiments had process-related variables that weren't directly incorporated in the mixture design. This comparatively lower predictability may be associated with the higher short fiber content and lower length uniformity of recycled cotton, which can introduce greater variability in yarn structure and extensibility, thereby influencing the elongation behavior of the blended yarns.

Although the number of experimental runs is relatively limited, the adopted extreme vertices mixture design is specifically developed to efficiently estimate quadratic mixture models within constrained design spaces. In this study, five replicated runs were intentionally included to provide an independent estimate of pure experimental error and to improve the robustness of statistical validation. To further assess potential overfitting, special attention was given to the relationship between R^2, adjusted R^2, and predicted R^2. The close agreement between R^2 and adjusted R^2, together with the consistently small differences (less than 20%) between adjusted and predicted R^2 for all responses, confirms that the developed models are not overfitted and possess satisfactory predictive capability within the experimental domain [45]. Although the predicted R^2 value for elongation (66.63%) is relatively lower than those of the other responses, the difference between adjusted R^2 and predicted R^2 is below 20% still indicating the satisfaction of the validation criterion.

The standard error of regression (S) shows how far off the predicted values are from the actual values on average. It is measured in the same units as each answer. Lower S values for hairiness and tenacity mean that the prediction bands are narrower. On the other hand, larger S values for IPI and CSP are in line with the fact that irregularity and strength-related data in recycled fiber spinning tend to be more spread out.

The PRESS values also back up the prediction evaluation. A lower PRESS means that the model can generalize better [46-48]. Responses with elevated predicted R^2 values have proportionally reduced PRESS, so affirming the coherence between cross-validated prediction error and explained variance.

In general, the results show that the quadratic mixture regression framework makes statistically sound and predictive models for all responses. It works especially well for tenacity, CSP, and hairiness, and it works moderately well for CVm%, IPI, and elongation, which shows how complicated and noise-sensitive these properties are.

Table 6. Model adequacy summary for all responses (quadratic mixture models)

Response	S	R^2 (%)	Adj. R^2 (%)	Pred. R^2 (%)	PRESS
CVm%	0.2428	90.88	85.18	74.29	1.3298
Imperfection Index (IPI)	73.42	89.95	83.68	71.96	120363
Hairiness	0.0373	93.29	89.10	79.78	0.0336
Count Strength Product (CSP)	22.13	90.54	84.62	81.56	7635.9
Tenacity	0.1952	93.94	90.16	81.08	0.9523
Elongation	0.1856	85.57	76.55	66.63	0.6372

Response surface equations interpretation

The quadratic mixing equations show how the amounts of recycled cotton (X1), eco-viscose (X2), and modal (X3) affect the quality of the yarn, as long as X1+X2+X3=100. Linear coefficients show how much each fiber adds to the mix, while interaction terms show how the fibers mix in a way that isn't straight [49], [50]. For a three-component fiber blend, the quadratic mixture regression model can be expressed as Equation (1)

$$Y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \quad \text{subject to} \quad x_1 + x_2 + x_3 = 100 \tag{1}$$

where Y represents the predicted response variable, x_1 , x_2 , and x_3 denote the proportions of recycled cotton, eco-viscose, and modal fibers, respectively, and βi and βij represent the regression coefficients of

the linear and interaction terms. Recycled cotton has a strong positive effect on CVm%, IPI, and hairiness. This means that as the amount of recycled fiber increases, the yarn becomes more uneven and the surface sticks out more. Eco-viscose and modal, on the other hand, lower reactions associated to irregularity, which shows that their fibers are more homogeneous and stick together better. The unfavorable interaction terms with recycled cotton support the idea that mixing regenerated fibers might help lessen these detrimental impacts. Regenerated fibers improve CSP and tenacity, with modal having the largest benefit. On the other hand, recycled cotton weakens yarn strength. The interaction terms show that fiber compatibility is very essential. Too much recycled cotton makes regenerated fibers less effective at reinforcing. The elongation reaction shows conflicting results: recycled cotton and eco-viscose have a positive impact, while modal has a little negative effect. This shows how hard it is to find the right balance between fibre extensibility and structural stiffness. The response surface equations indicate that the quality of yarn is determined by both the qualities of the individual fibers and how they interact with each other in pairs. The quadratic mixture model also shows how recycled–regenerated fiber blends behave in a non-linear way (shown in Table 7).

Table 7. Response Surface Equations

$CVm\% = 0.4932x_1 + 0.1599x_2 + 0.1900x_3 - 0.00406x_1x_2 - 0.00435x_1x_3 - 0.00107x_2x_3$	(i)
$IPI = 315.313x_1 + 17.583x_2 + 0.578x_3 - 4.919x_1x_2 - 4.739x_1x_3 + 0.740x_2x_3$	(ii)
$Hairiness = 0.6957x_1 + 0.0669x_2 + 0.00221x_3 - 0.01044x_1x_2 - 0.01076x_1x_3 + 0.00360x_2x_3$	(iii)
$CSP = 134.039x_1 + 35.307x_2 + 17.757x_3 - 2.270x_1x_2 - 1.782x_1x_3 + 0.433x_2x_3$	(iv)
$Tenacity = -4.6101x_1 + 0.0670x_2 + 0.7128x_3 + 0.07876x_1x_2 + 0.07777x_1x_3 - 0.03087x_2x_3$	(v)
$Elongation = 1.7848x_1 + 0.1689x_2 - 0.0906x_3 - 0.03097x_1x_2 - 0.02763x_1x_3 + 0.01047x_2x_3$	(vi)
$x_1 = r - Cotton\%$, $x_2 = Eco - Viscose\%$ and $x_3 = Modal\%$	

The statistical significance and adequacy of the developed quadratic mixture regression models were evaluated using analysis of variance (ANOVA). The ANOVA results summarized in Table X indicate that all regression models are statistically significant ($p < 0.05$). The lack-of-fit test results indicate that the models for hairiness, CSP, tenacity, and elongation adequately represent the experimental data ($p > 0.05$). However, significant lack-of-fit is observed for CVm% and IPI ($p < 0.05$), suggesting that the developed quadratic models do not fully capture the variability associated with these responses. This behavior can be attributed to the inherently higher variability of yarn irregularity and imperfection-related properties, particularly in recycled fiber blends where short fiber content, fiber damage, and process fluctuations introduce additional randomness. Despite

this limitation, the models still provide useful predictive trends within the studied design space, as supported by reasonable predicted R^2 values and validation results.

Table 8. ANOVA results for quadratic mixture models of yarn responses

Response	Model DF	F-value	p-value	Model significance	Lack-of-fit F-value	Lack-of-fit p-value	Lack-of-fit significance
CVm (%)	5	15.95	0.001	Significant	31.50	0.001	Significant
IPI	5	14.33	0.001	Significant	24.20	0.002	Significant
Hairiness	5	22.26	<0.001	Significant	1.94	0.241	Non-significant
CSP	5	15.31	0.001	Significant	0.04	0.989	Non-significant
Tenacity	5	24.82	<0.001	Significant	3.42	0.109	Non-significant
Elongation	5	9.49	0.003	Significant	1.06	0.445	Non-significant

Actual vs Predicted Value

Fig. 5 compares the experimentally measured values with the corresponding model-predicted values for all yarn quality responses, including CVm%, imperfection index (IPI), hairiness, count strength product (CSP), tenacity, and elongation. In all cases, the data points are distributed close to the 45° reference line, indicating good agreement between predicted and observed values.

CVm% and IPI (Figs. 5a–b), a relatively wider scatter around the reference line is observed, which can be attributed to the inherently higher variability associated with yarn irregularity and imperfection-related properties in recycled fibre blends. In contrast, hairiness and CSP (Figs. 5c–d) exhibit a tighter clustering along the reference line, reflecting stronger predictive accuracy for surface and strength-related responses.

Similarly, tenacity and elongation (Figs. 5e–f) show satisfactory linear correspondence between experimental and predicted values across the studied mixture domain. Overall, the predicted-versus-actual plots confirm the adequacy and predictive reliability of the developed quadratic mixture models for subsequent optimization analysis.

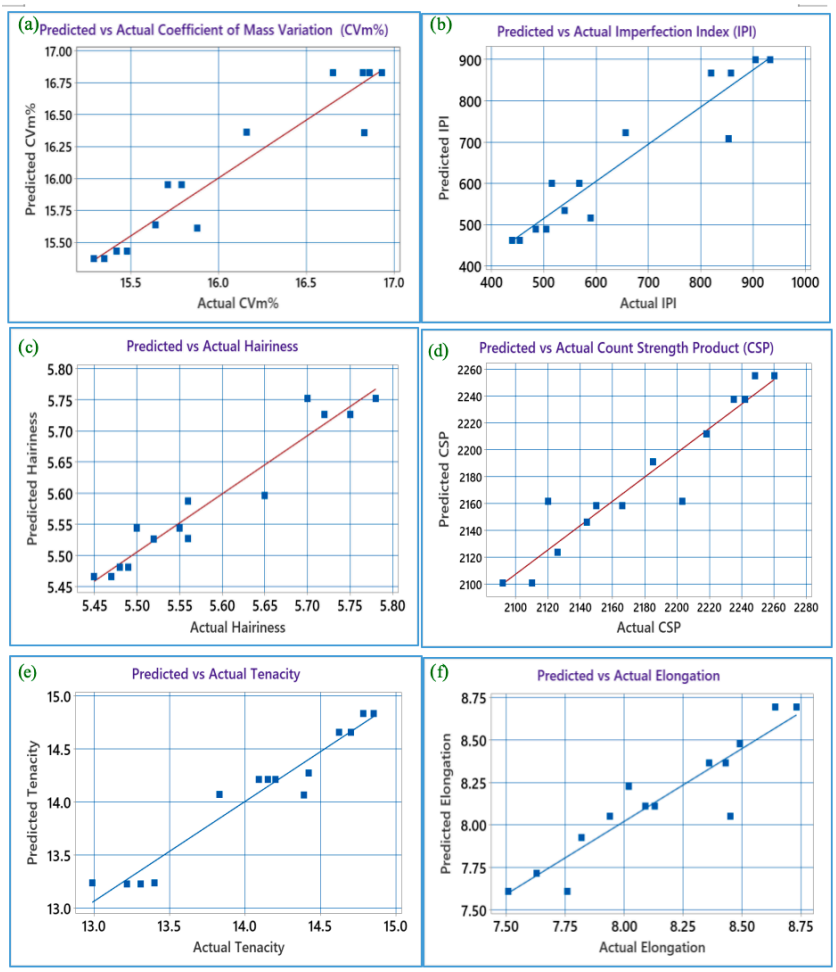


Figure 5. Comparison between experimentally measured and model-predicted values for (a) CVm%, (b) imperfection index (IPI), (c) hairiness, (d) count strength product (CSP), (e) tenacity, and (f) elongation (%).

Relationship between mixture components and yarn characteristics

In the following subsections, ternary contour plots and corresponding response surface plots are used to illustrate the influence of recycled cotton, eco-viscose, and modal proportions on yarn properties. In the ternary diagrams, each vertex represents one blend component, while contour lines and surface gradients indicate the variation of the response within the feasible mixture region.

Dependence of mixture components on unevenness and IPI of yarn

Yarn unevenness is commonly measured using the coefficient of mass variation (CVm%). In addition, yarn quality is also assessed by imperfection index (IPI) which is the summation of thin places, thick places, and neps in one km length. Yarns with high CVm% and IPI are more prone to breakage during winding, warping, sizing, weaving, or knitting, leading to increased end-breakages and reduced productivity[51-52].

The mixture contour plot of CVm% and IPI depicted in Fig. 6 (a & b) and the mixture surface plot, shown in Fig. 6 (a′ & b′) respectively, visually demonstrates how the relative proportions of recycled cotton, eco-viscose, and modal influence CVm% (response: Y1) and IPI (response: Y2) in the blend yarn. The regions with lower CVm% and IPI indicate that a well-balanced composition, particularly with a lower proportion of recycled cotton, and higher proportions of eco-viscose and modal reduce yarn unevenness and IPI.

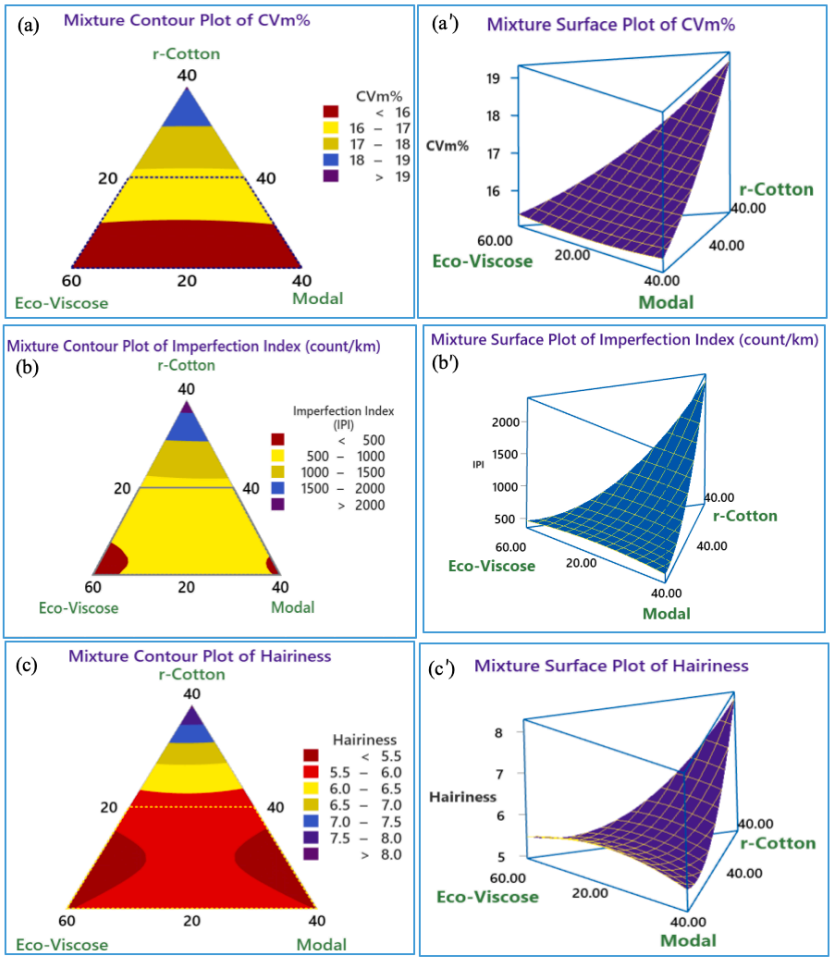


Figure 6. Mixture contour plot and surface plot showing the influence of mixture components on the (a & a′) coefficient of mass variation (CVm%), (b & b′) imperfection index (IPI), and (c & c′) hairiness of yarns.

Dependence of mixture components on the hairiness of yarn

Yarn hairiness refers to fibers protruding from the yarn surface. Although a limited degree of hairiness may enhance fabric softness and comfort, excessive or uneven hairiness adversely affects yarn appearance, abrasion resistance, pilling behavior, and print quality [53-55].

The mixture response analysis indicates that yarn hairiness increases with increasing recycled cotton content and decreases with higher proportions of eco-viscose and modal fibers. This behavior is primarily attributed to the higher short-fiber and nep content of recycled cotton, which originates from the mechanical shredding of pre-consumer textile waste [52]. AFIS results (Table 9) confirm that recycled cotton exhibits lower upper-quartile length and poorer length uniformity compared with regenerated fibers.

Although carding and subsequent drawing stages remove a portion of neps and short fibers, blends containing higher recycled cotton still retain sufficient fiber heterogeneity to promote fiber protrusion during spinning. As a result, yarns with elevated recycled cotton content exhibit higher hairiness, whereas eco-viscose and modal fibers improve fiber alignment and cohesion, effectively suppressing hairiness.

Table 9. AFIS test reports of 100% recycled cotton, 100% Eco-Viscose, 100% Modal, mixing (blow room delivery or card feed) and finisher draw frame (D/F) slivers consisted of recycled cotton, eco-viscose and modal fibre.

Material	Recycled fiber: Eco-Viscose: Modal	Fiber neps (FN)/g	FN size [µm]	Seed-coat neps (SCN)/g	SCN size [µm]	Upper Quartile Length (UQL) [mm]	Short fiber content, SFC (w) %
100% Recycled cotton (in bale)	100:0:0	675	724	49	1430	23.2	16.7
100% Eco-Viscose (in bale)	0:100:0	79	627	3	800	38.2	0.2
100% Modal (in bale)	0:0:100	62	619	2	817	38.27	0.3
Card feed of tri-blends	20:40:40	162	656	26	13057	35.9	10.25
	22.5: 43.75: 33.75	196	676	28	1309	36.2	10.41
	25: 47.5: 27.5	205	685	32	1324	36.3	10.82
	27.5: 43.75: 28.75	261	692	38	1337	36.2	11.29
	30:50:20	276	698	48	1355	36.2	13.11
Finisher D/F slivers of tri-blends	20:40:40	13	528	2	744	37.6	8.40
	22.5: 43.75: 33.75	17	545	2	770	37.6	8.80
	25: 47.5: 27.5	19	556	3	782	37.5	8.80
	27.5: 43.75: 28.75	20	564	3	786	37.4	9.30
	30:50:20	22	572	3	797	37.4	10.90

A review of fiber characteristics in Table 1 (HVI) and Table 9 (AFIS) confirms that recycled cotton fibers are significantly shorter and contain a higher proportion of short fibers compared with eco-viscose and modal. In ring spinning, the spinning triangle formed immediately after the front roller nip exposes fibers to non-

uniform tension, where shorter edge fibers are less effectively incorporated into the yarn body, leading to increased surface hairiness [56-57]. Additionally, during yarn ballooning, shorter and coarser fibers tend to migrate toward the yarn surface, whereas longer and finer fibers preferentially migrate toward the core [58]. The comparatively higher fiber fineness of recycled cotton (4.5 µg/inch) relative to eco-viscose (≈3.37 µg/inch) and modal (≈3.30 µg/inch) further contributes to elevated hairiness at higher recycled cotton proportions, a trend that is also evident from the SEM images shown in Fig. 7.

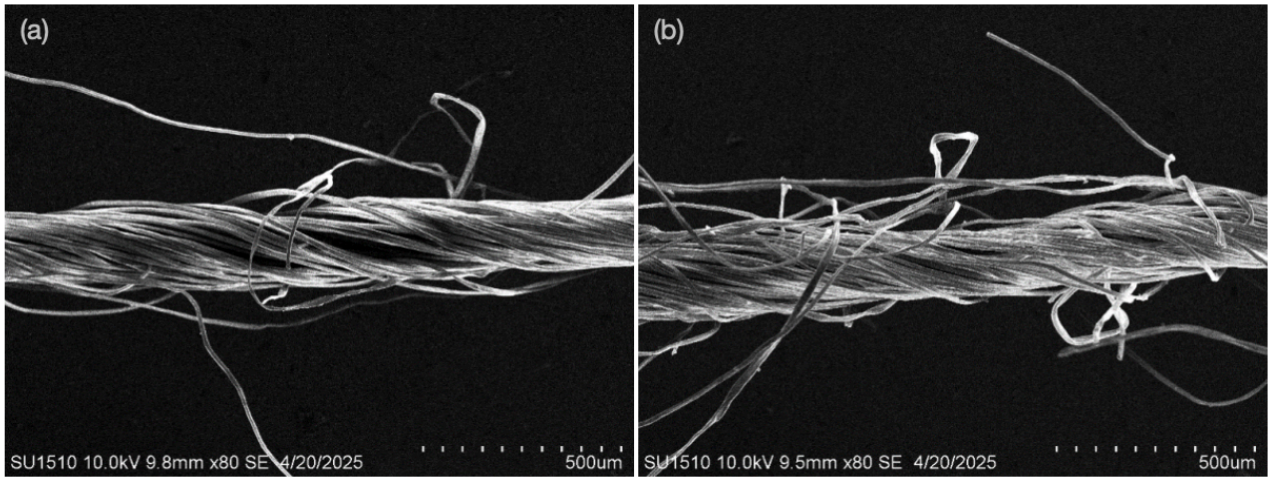


Figure 7. SEM images of yarns produced with (a) 20% and (b) 30% recycled cotton content in the blend.

Dependence of mixture components on the strength (CSP and tenacity) of yarn

To make sure that textiles are of good quality and work well, it is important to check the strength of the yarn. The Count Strength Product (CSP), calculated as the product of yarn count (Ne) and lea strength (lb), reflects overall bundle strength and is useful for comparing yarns of similar counts. Tenacity, which is measured in g/tex or cN/tex, tells you how much power it takes to break a yarn based on its linear density. This lets you compare various kinds and counts of yarn [59]. Used together, CSP and tenacity provide a comprehensive assessment of yarn strength and tensile resistance, supporting reliable performance in textile applications [60-61].

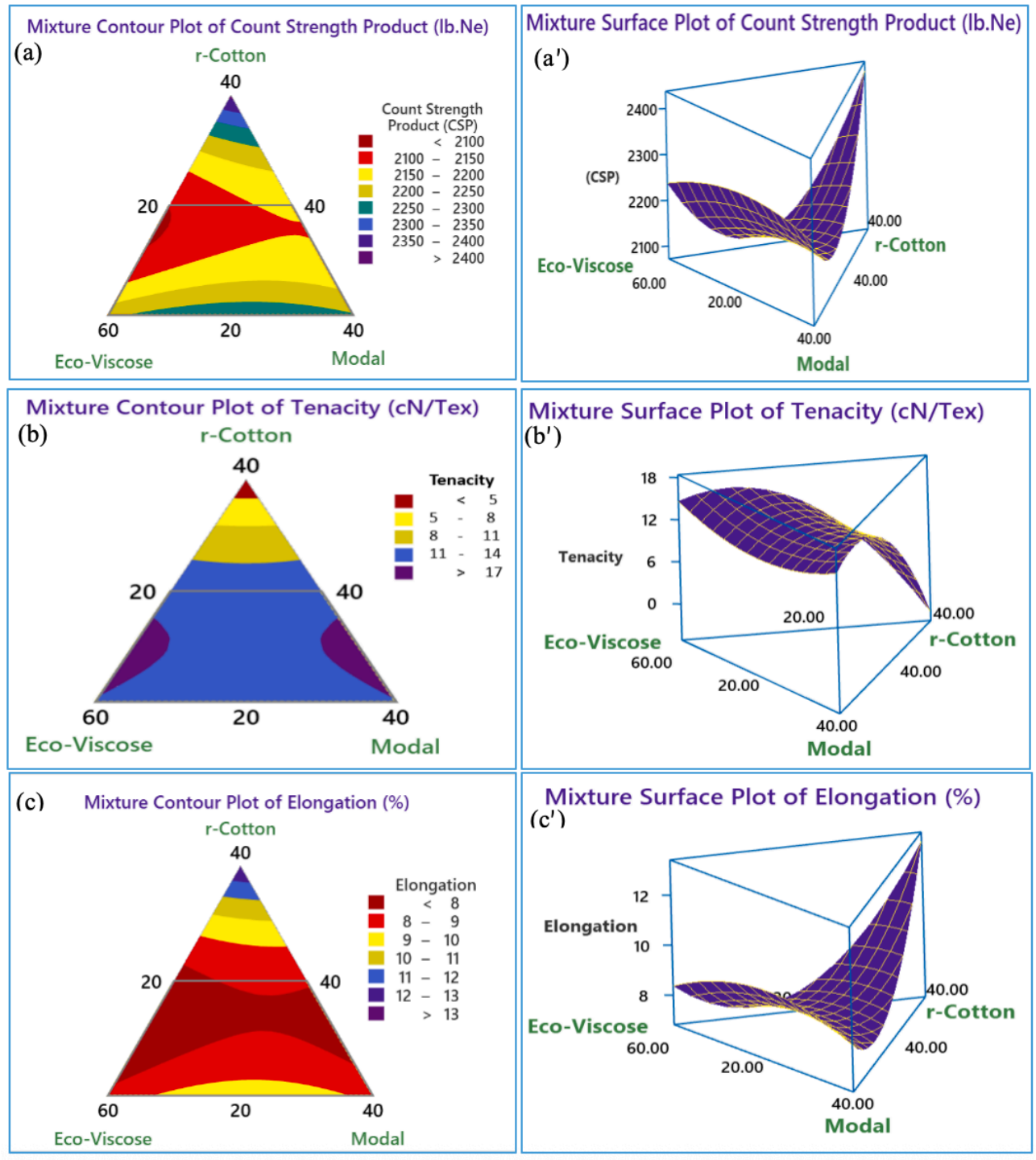


Figure 8. Mixture contour plots and surface plots showing the influence of mixture components on (a & a′) CSP, (b & b′) tenacity (cN/tex) and (c & c′) elongation at break% of yarns.

Fig. 8(a & a′) and Fig. 8(b & b′) present the mixture contour plot and mixture surface plot, respectively, for CSP and tenacity illustrating that a greater content of recycled cotton tends to lower CSP and tenacity, while higher proportions of modal and eco-viscose improve them. However, the steady decrease in both CSP and tenacity

as the proportion of recycled fibers in the yarn increases, corresponds with the rise in yarn unevenness and imperfections shown in Fig. 6. This decline is primarily attributed to the shorter fiber length and higher short fiber content found in recycled cotton. Unlike longer fibers, short fibers struggle to properly bind and migrate within the yarn structure. When subjected to tensile stress, shorter fibers have a limited ability to bear the load and are more prone to slippage, which ultimately decreases the overall yarn strength.

It is important to note that several pre-treatment methods, including scouring, bleaching, and mercerization, followed by dyeing, usually change the microstructure of cellulose. For example, they might make it less crystalline, which weakens cotton fibers [62-63]. Because of this, virgin cotton usually has tenacity values between 30 and 42 g/tex [64]. However, the aggressive shredding operation done by several beaters on colored garment cut clips turns recycled cotton into something much weaker, as shown by the results of this study (HVI results, Table 1). These weaker recycled fibers are more likely to break when cleaning machines (blow room and carding) beat them, which makes the finished yarn weaker. In addition, the modified surface frictional behavior of dyed fibers disrupts fiber flow and slippage during drafting, leading to irregular drafting, which negatively contributes to yarn unevenness and imperfections as well as strength [65-66].

Dependence of mixture components on breaking elongation of yarn

Elongation is a key mechanical property of yarn alongside strength. In warping, sizing and weaving, warp yarns must possess sufficient elongation to absorb applied tensions and dynamic stresses without breaking. Elongation is equally important in knitting, where yarns undergo repeated bending, looping, and stretching. Although yarn elongation primarily depends on the extensibility of constituent fibers, inter-fiber cohesion, yarn structure, and manufacturing processes also play significant roles in determining its overall elongation behavior of yarns [55].

The contour plot and surface plots shown respectively in Fig. 8 (c and c′) demonstrate that eco-viscose and modal are the primary factors contributing to higher elongation. As their proportions rise, the elongation (response Y6) significantly increases. Conversely, when recycled cotton is present in higher amounts relative to eco-viscose and modal, elongation decreases.

The higher yarn elongation in presence of higher eco-viscose and modal content is attributed to their inherently higher fiber elongation values (eco-viscose: ~17% and modal: 14% as shown in Table 1). In contrast, the lower yarn elongation associated with a higher recycled cotton ratio is due to its lower fiber elongation (7% as mentioned in Table 1).

Multi-response optimization and experimental validation

Quadratic mixture models developed in the preceding sections were employed to identify the optimal blend composition of recycled cotton, eco-viscose, and modal by simultaneously considering multiple yarn quality responses. A desirability function–based multi-response optimization strategy was applied to minimize yarn unevenness (CVm%, Y1), imperfection index (IPI, Y2), and hairiness (Y3), while maximizing count strength product (CSP, Y4), tenacity (Y5), and elongation at break (Y6). The optimization objectives, response limits, and weighting criteria for each response variable are summarized in Table 10.

Table 10. Optimization criteria

	Code	Name	Range	Goal Criteria
Fiber Component	X1	Recycled cotton	20-30	Optimize
	X2	Eco-Viscose	40-60	Optimize
	X3	Modal	20-40	Optimize
Response	Y1	CVm%	14.74–16.93	Minimize
	Y2	IPI	268–933	Minimize
	Y3	Hairiness	5.40–5.78	Minimize
	Y4	CSP	2092–2295	Maximize
	Y5	Tenacity	12.99–15.79	Maximize
	Y6	Elongation at break	7.50–8.90	Maximize

The numerical optimization results shown in Fig. 9 show that a high composite desirability value (D = 0.8258) may be reached within the mixing limitations that were set. The best mix was found to be 20.3030% recycled cotton, 40.00% eco-viscose, and 39.6970% modal. This was the best balance between the needs of the yarn quality and the need to use fibers in a way that is good for the environment. Table 11 shows the model-predicted values of all six answers at this best point.

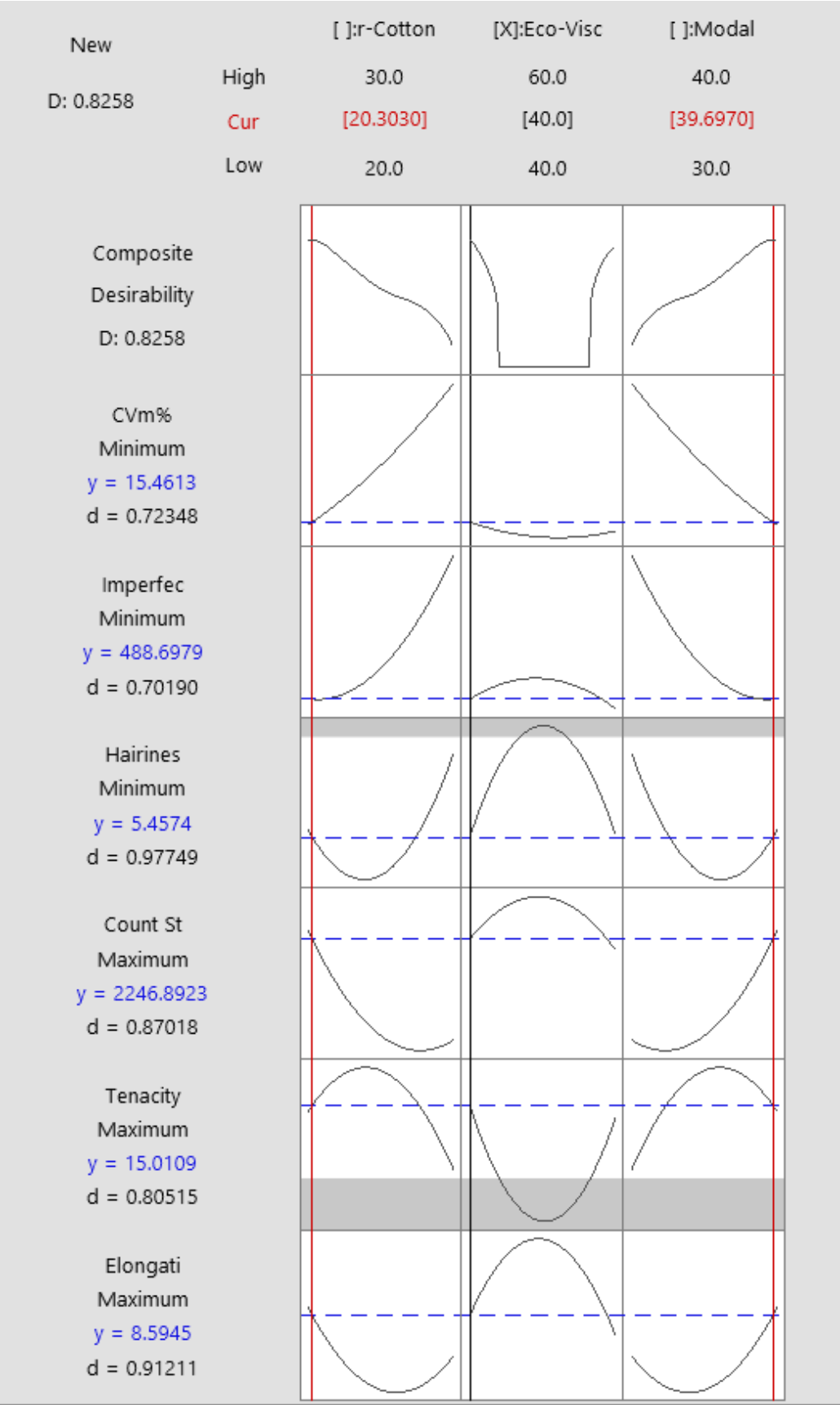


Figure 9. Numerical optimization of mixture components using desirability functions

Table 11. Optimized blend ratio and predicted responses obtained from multi-response optimization.

Components	Value
Recycled Cotton	20.30%
Eco-Viscose	40.00%
Modal	39.70%
Responses	Value
CVm (%)	15.46
IPI	489
Hairiness	5.46
CSP	2247
Tenacity (cN/tex)	15.01
Elongation at break (%)	8.59

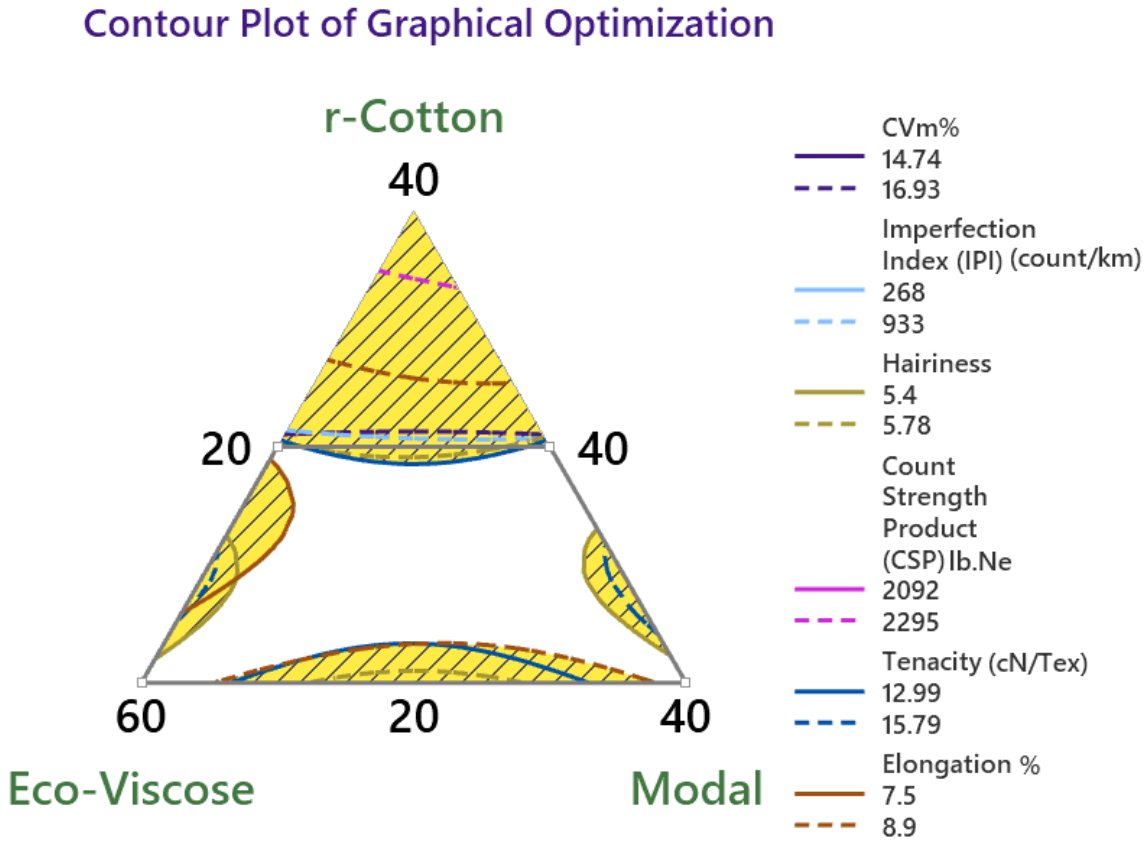


Figure 10. Overlaid contour plot illustrating the feasible optimization region for the selected yarn quality responses

Fig. 10 shows the ternary contour plots for the optimum composition, which show how the optimized blend responds in the viable mixing range. These graphs show that the chosen blend is in a stable area where the quality of the yarn reactions is close to their best levels at the same time, not at the edges of the combination

space. This picture shows that the optimization result is strong and that modest changes around the optimized mix are not likely to produce a sudden drop in yarn performance.

To validate the optimization results, yarns were produced experimentally using the optimized blend composition under identical spinning conditions and ten bobbin specimens were tested for each response. The reported experimental values represent the mean of these measurements, thereby providing a reliable estimate of the yarn properties. The experimentally measured yarn properties were then compared with the corresponding model-predicted values. As summarized in Table 12, the deviations between predicted and experimental results remained within acceptable limits for all responses, confirming the adequacy and predictive capability of the developed quadratic mixture models. Minor discrepancies observed for certain responses are attributed to the inherent variability of recycled cotton fibers and unavoidable process fluctuations during industrial ring spinning.

Table 12. Comparison between the estimated and experimentally measured yarn properties of the optimized tri-blend yarn composition

Response	Predicted value (a)	Actual value (b)	Difference[(a-b)/a]%
CVm%	15.46	15.62	1.03%
IPI	488.70	513	4.97%
Hairiness	5.46	5.54	1.47%
CSP	2247	2231	0.71%
Tenacity	15.01	14.92	0.60%
Elongation	8.59	8.61	0.23%

The combined findings of optimization, visualization, and experimental validation show that the right mix of recycled cotton and regenerated fibers may provide yarns with good physical and mechanical qualities while making the most of recycled fibers. So, the suggested optimization framework provides a solid and useful guidance for choosing sustainable yarn blends while spinning in an industrial setting. The optimized tri-blend yarn contributes to improved resource efficiency by incorporating recycled cotton and eco-viscose, which are reported in the literature to have lower environmental impacts compared to conventional cotton and viscose fibers. The use of recycled cotton reduces dependence on virgin fiber production, while eco-viscose is produced using more environmentally responsible processes. However, it should be noted that a detailed life cycle assessment (LCA) and quantitative evaluation of environmental benefits, such as reductions in water consumption, energy use, and carbon emissions, were not conducted in this study. Therefore, the

sustainability implications discussed here are qualitative and based on material selection rather than quantified environmental metrics. Future work should focus on comprehensive LCA to validate the environmental performance of the proposed blend system.

Cost-effectiveness for Eco-viscose/Recycled cotton/Modal tri-blend Yarn

To evaluate the economic feasibility of the developed yarn, a cost comparison was performed between the optimized sustainable tri-blend yarn and a corresponding conventional yarn with the same blend proportions. In the benchmark case, recycled cotton and eco-viscose were replaced by virgin cotton and regular viscose, respectively, while maintaining the optimized blend ratio (40.0% viscose, 20.3% cotton, and 39.7% modal). Natural fibers like cotton are getting harder to find and more expensive, so more and more people around the world are interested in using sustainable fibers made from textile waste and recycled materials [56,67]. This is because the cost of raw materials is a big part of the total cost of making yarn. In this context, the current study sought to augment the ratio of eco-viscose and recycled cotton in yarn production to create yarns that are economically viable, environmentally sustainable, and industrially feasible, while mitigating the environmental and health issues linked to traditional cotton cultivation and viscose production. So, recycled cotton was chosen to replace virgin cotton, and eco-viscose was chosen to replace normal viscose.

The cost of making 30 Ne tri-blend yarns made from recycled cotton, eco-viscose, and modal was compared to the cost of making ordinary yarns made from virgin cotton, regular viscose, and modal. Table 13 shows the full cost breakdown, which includes the prices of raw materials, the cost of processing waste, the resale value of trash, and the overhead costs of production. The findings show that eco-viscose is cheaper than conventional viscose and that recycled cotton costs around half as much as virgin cotton. The price of recycled cotton, on the other hand, might change based on things like where the trash came from (before or after it was used), the color of the fabric, and the method used to recycle or shred it.

The cost analysis was done in Bangladesh's industrial setting and looked at important production factors like ring frame speed, yarn twist multiplier, energy use, labor costs, processing waste, and capital costs like machinery, land, depreciation, interest, and administrative overheads. When recycled cotton was used, the spinning speed had to be slowed down to avoid breaking the yarn, and the amount of processing waste went up since there were more short fibers and neps. The cost of making these things took into consideration all of the operating problems.

Although the incorporation of recycled cotton leads to higher processing waste and a modest increase in manufacturing overhead, the optimized eco-viscose/recycled cotton/modal tri-blend yarn shows only a slight rise in production cost (3.52 USD/kg) compared with the conventional virgin cotton/regular viscose/modal yarn (3.27 USD/kg), as presented in Table 13. This marginal increase is mainly driven by the higher cost of eco-viscose (2.68 USD/kg) relative to regular viscose (1.80 USD/kg).

Nevertheless, the integration of recycled cotton and eco-viscose substantially reduces reliance on virgin raw cotton, thereby lowering the overall environmental burden. Consequently, despite the minor cost escalation, the proposed tri-blend yarn aligns with sustainable manufacturing practices effective waste recycling and resource reuse.

Table 13. 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)	20.30 30% Virgin Cotton+40% Regular Viscose+39.69 70% Modal	20.30 30% Recycled Cotton+40% Eco-Viscose+39.69 70% Modal
Virgin cotton (Cameroon)(a)	2.25	0.46	–
Regular Viscose(b)	1.80	0.72	–
Modal(c)	2.70	1.07	1.07
*Recycled Cotton(d)	1.12	–	0.23
Eco-Viscose(e)	2.68	–	1.07
Total raw materials (f) =		2.25	
Processing waste (g)		12%	15%
Raw material cost considering waste, (h) = (f)/(1-g)		2.56	2.79
**Waste price, (i)	0.80	0.80	0.80
Net Raw Material Cost, (j)=(h)-(i)		1.76	1.99
***Manufacturing overhead(k)		1.51	1.53
Total Yarn Cost, (j)+(k)		3.27 USD/kg	3.52 USD/kg

* The price of recycled cotton fluctuates over time based on the color, source and processing methods.

** The spinning waste comprising of multiple fibers holds a good sale value in the local market to produce domestic goods like pillows, quilts, and mattresses

***Manufacturing overhead includes indirect costs such as utilities, salaries, depreciation. It rises slightly for processing the recycled cotton due to the necessity of reducing machine speed to ensure smooth operation.

CONCLUSION

This study demonstrates a sustainable approach to producing tri-blend yarns by combining eco-viscose, recycled cotton, and modal fibers. Recycled cotton was used to replace virgin cotton, while modal compensated for the associated reduction in yarn strength. Response surface methodology based on an extreme vertices mixture design was applied to determine the optimal blend composition. Fourteen yarn samples with different blend ratios were produced and analyzed using regression and ANOVA. The developed models showed good predictive capability within the defined mixture constraints.

The optimal blend, consisting of 20.30% recycled cotton, 40.00% eco-viscose, and 39.70% modal, produced yarn properties that closely matched the predicted values obtained from the developed regression models. The quadratic mixture models demonstrated strong predictive capability for the investigated responses. The experimentally validated yarn exhibited acceptable levels of unevenness, imperfection index, hairiness, strength, and elongation, confirming its suitability for processing on a commercial high-speed knitting machine. These findings demonstrate the feasibility of producing sustainable tri-blend yarns with balanced performance using recycled cotton and regenerated cellulosic fibers.

Future research may focus on applying advanced predictive tools such as machine learning and artificial neural networks to further improve yarn property prediction and process optimization. In addition, detailed evaluation of fabric performance and long-term durability of the developed sustainable blends is recommended.

Overall, the development of the tri-blend yarn reduces dependence on conventional viscose production and resource-intensive cotton cultivation and processing, thereby contributing to environmental conservation. Furthermore, this approach aligns with sustainable manufacturing practices and supports Sustainable Development Goals Goal 12 by promoting responsible consumption and production through effective waste recycling and resource reuse.

Authors' contribution

MMA: Conceptualization, methodology, validation, resources, writing original draft; MRH: Conceptualization, methodology, validation, software, formal analysis, data curation, writing original draft; AJU: Conceptualization, methodology, overall supervision, Writing, reviewing and editing. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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Data availability statement

Data will be made available on request.

Declarations

Ethics and consent to participate: Not applicable.

REFERENCES

[1] Arimany Serrat N, Arribas-Ibar M, Erdoğan G. Fast fashion sector: business models, supply chains, and European sustainability standards. Systems. 2025; 13(6): 405. doi: 10.3390/systems13060405

[2] Herold P I, Prokop D. Is fast fashion finally out of season? Rental clothing schemes as a sustainable and affordable alternative to fast fashion. Geoforum. 2023; 146: 103873. doi: 10.1016/j.geoforum.2023.103873

[3] Huang Y, Zhang K, Deng X, et al. Fast fashion consumption signals low self-control. Journal of Consumer Research. 2026; 52(6): 1253-1273. doi: 10.1093/jcr/ucaf032

[4] Bartl A, Ipsmiller W. Fast fashion and the Circular Economy: Symbiosis or antibiosis? Waste Management & Research. 2023; 41(3): 497-498. doi: 10.1177/0734242X221149639

[5] Huang X, Tan Y, Huang J, et al. Industrialization of open-and closed-loop waste textile recycling towards sustainability: A review. Journal of Cleaner Production. 2024; 436: 140676. doi: 10.1016/j.jclepro.2024.140676

[6] Lee J C, Huh M W, Hou Y L, et al. Complex challenges in the textile industry and potential solutions in photocatalytic coating technology: a systematic literature review. Materials. 2025; 18(4): 810. doi: 10.3390/ma18040810

[7] Wang J F, Zhang Y, Hult G T M, et al. Leveraging customer learning and time-based targeting for fast fashion new arrivals. Journal of Retailing and Consumer Services. 2025; 83: 104141. doi: 10.1016/j.jretconser.2024.104141

[8] Bläse R, Filser M, Kraus S, et al. Non-sustainable buying behavior: How the fear of missing out drives purchase intentions in the fast fashion industry. Business Strategy and the Environment. 2024; 33(2): 626-641. doi: 10.1002/bse.3509

[9] De Ponte C, Liscio M C, Sospiro P. State of the art on the Nexus between sustainability, fashion industry and sustainable business model. Sustainable Chemistry and Pharmacy. 2023; 32: 100968. doi: 10.1016/j.scp.2023.100968

[10] Islam S, Rahman S, Mazumder B C, Mohin A A, Islam I, Hoque A. The Effect of Different Mordants on Silk and Cotton Fabric Dyed with Mahogany (Swietenia macrophylla) Seed Pods by Using the Exhaust Method. Fibers and Polymers. 2025; 1-14. doi: 10.1007/s12221-025-01207-5

[11] Chen X, Memon H A, Wang Y, et al. Circular economy and sustainability of the clothing and textile industry. Materials Circular Economy. 2021; 3(1): 12. doi: 10.1007/s42824-021-00026-2

[12] Garcia-Ortega B, Galan-Cubillo J, Llorens-Montes F J, et al. Sufficient consumption as a missing link toward sustainability: The case of fast fashion. Journal of cleaner production. 2023; 399: 136678. doi: 10.1016/j.jclepro.2023.136678

[13] Mazumder B C, Elamoni KN, Proma JS, Sayed NI, Mofasser AZM, Mia R. Biotechnology Advances in the Pre-Treatment Processes in the Textile Dyeing Industry.In: Biotechnology Approaches in Textile Technology. CRC Press. 2025; 48-49. doi: 10.1201/9781003677840-3

[14] Akter M M K, Haq U N, Islam M M, et al. Textile-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh. Cleaner Environmental Systems. 2022; 4: 100070. doi: 10.1016/j.cesys.2022.100070

[15] Reza M M, Begum H A, Uddin A J. Potentiality of sustainable corn starch-based biocomposites reinforced with cotton filter waste of spinning mill. Heliyon. 2023; 9(5). doi: 10.1016/j.heliyon.2023.e15697

[16] Chapagain A K, Hoekstra A Y, Savenije H H G, et al. The water footprint of cotton consumption. Value of Water Research Report Series. 2010; 18. doi: 10.1002/9780470696224.ch9

[17] Jans Y, von Bloh W, Schaphoff S, et al. Global cotton production under climate change–Implications for yield and water consumption. Hydrology and earth system sciences. 2021; 25(4): 2027-2044. doi: 10.5194/hess-25-2027-2021

[18] Raiskio S, Periyasamy A, Hummel M, et al. Transforming mechanically recycled cotton and linen from post-consumer textiles into quality ring yarns and knitted fabrics. Waste Management Bulletin. 2025; 3(1): 76-86. doi: 10.1016/j.wmb.2024.12.006

[19] Zhang Z, Huang J, Yao Y, et al. Environmental impacts of cotton and opportunities for improvement. Nature Reviews Earth & Environment. 2024; 4:703-715. doi: 10.1038/s43017-023-00476-z

[20] Rehan M, Mashaly H M, Abdel-Aziz M S, et al. Viscose fibers decorated with silver nanoparticles via an in-situ green route: UV protection, antioxidant activities, antimicrobial properties, and sensing response. Cellulose. 2024; 31(9): 5899-5930. doi: 10.1007/s10570-024-05856-2

[21] Forsberg D C R, Bengtsson J, Hollinger N, et al. Towards sustainable viscose-to-viscose production: strategies for recycling of viscose fibres. Sustainability. 2024; 16(10): 4127. doi: 10.3390/su16104127

[22] Uddin A J, Roy P. Transforming melange fabric waste into mélange yarn employing compact, Siro, and compact-Siro spinning: A cleaner and sustainable strategy. Cleaner Waste Systems. 2024; 8: 100142. doi: 10.1016/j.clwas.2024.100142

[23] Wang X, Jiang J, Gao W. Reviewing textile wastewater produced by industries: characteristics, environmental impacts, and treatment strategies. Water Science and Technology. 2022; 85(7): 2076-2096. doi: 10.2166/wst.2022.088

[24] Gaafer R R. Utilizing Circulose fibers in the production of denim fabrics in the context of textile waste management: A case study in DNM textile factory. International Design Journal. 2025; 15(5): 151-162. doi: 10.21608/idj.2025.389941.1344

[25] Photopoulos J. Spinning sustainability: meet the physicists turning wood into clothes. Physics World. 2023; 36(11): 37-40. doi: 10.1088/2058-7058/36/11/23

[26] Kumar P, Sai Ram C, Srivastava J P, et al. Synthesis of cotton fiber and its structure. Natural and Synthetic Fiber Reinforced Composites: Synthesis, Properties and Applications. 2022: 17-36. doi: 10.1002/9783527832996.ch2

[27] Ruiz-Caldas M X, Carlsson J, Sadiktsis I, et al. Cellulose nanocrystals from postconsumer cotton and blended fabrics: a study on their properties, chemical composition, and process efficiency. ACS Sustainable Chemistry & Engineering. 2022; 10(11): 3787-3798. doi: 10.1021/acssuschemeng.2c00797

[28] Ahmed W A H, MacCarthy B L. Blockchain-enabled supply chain traceability in the textile and apparel supply chain: A case study of the fiber producer, Lenzing. Sustainability. 2021; 13(19): 10496. doi: 10.3390/su131910496

[29] Tomljenović A, Živičnjak J. Comparative Property Analysis of One-by-One Rib Lingerie Fabrics Fabricated from Modal Fibers and Microfibers. Nanomaterials. 2025; 15(9): 653. doi: 10.3390/nano15090653

[30] Latif W, Basit A, Rehman A, et al. Study of mechanical and comfort properties of modal with cotton and regenerated fibers blended woven fabrics. Journal of Natural Fibers. 2019; 16(6): 836-845. doi: 10.1080/15440478.2018.1441084

[31] Sigaard A S, Laitala K. Natural and sustainable? Consumers' textile fiber preferences. Fibers. 2023; 11(2): 12. doi: 10.3390/fib11020012

[32] Bidima II A M N, Efeze D N, Ebanda F B, et al. Modeling of mechanical behavior of Agave sisalana fiber's yarn using the design of experiments method. Results in Materials. 2024; 23: 100605. doi: 10.1016/j.rinma.2024.100605

[33] Aftab M, Ahmad T, Adeel S, et al. Hyper-parameter tuning through innovative designing to avoid over-fitting in machine learning modelling: a case study of small data sets. Journal of Statistical Computation and Simulation. 2025; 95(7): 1595-1609. doi: 10.1080/00949655.2025.2465787

[34] Aftab M, Ahmad T, Adeel S, et al. Ecofriendly process optimization of natural dye extraction from clove (Syzygium aromaticum L.) using response surface methodology and artificial neural network modeling. Sustainable Chemistry and Pharmacy. 2024; 37: 101401. doi: 10.1016/j.scp.2023.101401

[35] Hossen J, Islam M R, Saha S K, et al. Application of Artificial Neural Networks in yarn manufacturing industry: A critical review. Journal of Engineered Fibers and Fabrics. 2025; 20: 15589250251329415. doi: 10.1177/15589250251329415

[36] Altaye A, Farkas I, Víg P. Impacts of Artificial Neural Network Training Algorithms on the Accuracy of PV System Voltage and Current Predictions. European Journal of Energy Research. 2025; 5(3): 1-6. doi: 10.24018/ejenergy.2025.5.3.161

[37] Mazumder B C, Urmi N A, Mahmud M H, et al. Machine Learning (ML) and Artificial Intelligence (AI) in Textile Surface Modification. In: Advances in Surface Modification and Functionalization in Textiles. 2026; 247-272. doi: 10.1007/978-3-032-23377-6_10

[38] Hawlader M R, Islam M N, Sanzid L R, et al. Predictive modeling of yarn properties in sustainable fiber blends: A fuzzy linear regression approach. Waste Management Bulletin. 2026: 100293. doi: 10.1016/j.wmb.2026.100293

[39] Alam I K, Hawlader M R, Rahaman M, et al. Modeling and optimizing yarn characteristics in sustainable cotton blends through multiple linear regression and artificial neural networks. Cleaner and Circular Bioeconomy. 2026: 100210. doi: 10.1016/j.clcb.2026.100210

[40] Islam R, Uddin M B, Hawlader M R, et al. Employing response surface methodology in the production of sustainable PC yarn from recycled polyester and recycled cotton. Cleaner Waste Systems. 2025: 100421. doi: 10.1016/j.clwas.2025.100421

[41] Arafat Y, Uddin A J. Recycled fibers from pre-and post-consumer textile waste as blend constituents in manufacturing 100% cotton yarns in ring spinning: A sustainable and eco-friendly approach. Heliyon. 2022; 8(11). doi: 10.1016/j.heliyon.2022.e11275

[42] Enyegue T T O, Dairou M M, Bidima II A M N, et al. Multi-criteria assessment of recycled polyethylene terephthalate (PET) incorporation in bituminous mixtures: application to the cameroonian context. Transportation Research Interdisciplinary Perspectives. 2026; 36: 101869. doi: 10.1016/j.trip.2026.101869

[43] Delhom CD, Kelly B, Martin V. Physical Properties of Cotton Fiber and Their Measurement. In: Fang DD, editor. Cotton Fiber: Physics, Chemistry and Biology. Springer; 2018:41-73. doi:10.1007/978-3-030-00871-0_3

[44] Iqbal M, Sohail M, Ahmed A, et al. Textile environmental conditioning: effect of relative humidity variation on the tensile properties of different fabrics. Journal of Analytical Sciences, Methods and Instrumentation. 2012; 2(02): 92-97. doi: 10.4236/jasmi.2012.22017

[45] Montgomery D C. Design and analysis of experiments. John wiley & sons, 2017.

[46] Franklin J. The elements of statistical learning: data mining, inference and prediction. The Mathematical Intelligencer. 2005; 27(2): 83-85. doi: 10.1007/BF02985802

[47] Lorenz F, Neter J, Wasserman W, Kutner MH. Applied Linear Statistical Models. J Am Stat Assoc. 1986;81(396):1126. doi: 10.2307/2289108

[48] Sprent P, Gunst RF, Mason RL, Weisberg S. Regression Analysis and its Applications. CRC Press. 1982;38(3). doi: 10.2307/2530073

[49] Cornell J A. Experiments with mixtures: designs, models, and the analysis of mixture data. Wiley-interscience, 1843.

[50] Gunst RF, Myers RH, Montgomery DC. Response Surface Methodology: Process and Product Optimization Using Designed Experiments. Technometrics. 1996;38(3):285. doi:10.2307/1270613

[51] Uddin M N, Tumpa T R, Hawlader M R, et al. Advancing circular Textiles: MLR-Based optimization of tri-blend Melange yarns from sustainable fibers. Waste Management Bulletin. 2025: 100277. doi: 10.1016/j.wmb.2025.100277

[52] Uddin A J, Rahaman M. A sustainable and greener approach of transforming consumer-waste recycled fibers into value-added “grindle yarn” employing compact-Siro spinning. Journal of Engineered Fibers and Fabrics. 2024; 19: 15589250241270499. doi: 10.1177/15589250241270499

[53] Uddin M B, Uddin A J. A sustainable approach to manufacture mélange yarn from waste jute fiber and pre-consumer cotton fabric waste using I-optimal mixture design. Journal of Cleaner Production. 2023; 421: 138376. doi: 10.1016/j.jclepro.2023.138376

[54] Ahmed F, Mills A C, Kwon C H. Impact of weaving parameters on the performance of yarn-based interconnects in woven e-textiles: A comprehensive review. Journal of Engineered Fibers and Fabrics. 2025; 20: 15589250251372498. doi: 10.1177/15589250251372498

[55] Hossain MA, Srijan SK, Rinaz KR, Khan SQ, Uddin AJ. Investigations of the spinning consistency index (SCI) and its impact on yarn quality. Res J Text Appar. 2025;30(1):102-115. doi:10.1108/RJTA-07-2024-0129

[56] Islam M R, Mia R, Uddin A J. Investigation of the performance of okra fiber in woven fabric. Heliyon. 2022; 8(4). doi: 10.1016/j.heliyon.2022.e09307

[57] Xia Z, Wang H S, Ye W. A method to produce ring single yarn with fancy and anti-frictional structure by feeding filaments in front of the front roller nip..Textile Research Journal. 2020; 90(5-6): 631-640. doi: 10.1177/0040517519877466

[58] Uddin A J, Hossain M S. Underexploited Hemp Fiber as a Blend Constituent with Cotton in Producing Vortex Yarns: Toward a Sustainable and Cleaner Future. Cleaner Waste Systems. 2025: 100374. doi: 10.1016/j.clwas.2025.100374

[59] Uddin M B, Begum H A, Uddin A J. Elastic jute yarn suitable for stretch-denim. Cellulose. 2024; 31(11): 7031-7051. doi: 10.1007/s10570-024-05981-y

[60] Faysal G M, Hawlader M R, Mahmud T, et al. Sustainable Rotor Yarn Production From Knitting Industries Fabrics Wastes. Webology (ISSN: 1735-188X). 2021; 18(6).

[61] Hawlader M R, Nishi S I, Uddin M N, et al. A potential approach to analyze the optimum characteristics of cotton/modal & cotton/viscose blended yarn. Global Journal of Research in Engineering. 2018; 12(2): 9-12.

[62] Knihs A, Aragão L, Granato M, et al. Reduction Discoloration of Reactive Dyed Cotton Waste and Chemical Recycling via Ionic Liquid. Journal of Renewable Materials. 2024; 12(9): 1557. doi: 10.32604/jrm.2024.052963

[63] Zhao H, Zhang K, Fang K, et al. Insights into coloration enhancement of mercerized cotton fabric on reactive dye digital inkjet printing. Rsc Advances. 2022; 12(17): 10386-10394. doi: 10.1039/D2RA01053D

[64] Tian L, Xu Z, Zheng Z, et al. Analysis on the Production Advantages of USA Pima Extra Long Staple Cotton. Agricultural Science & Technology. 2017; 18(5): 892-903.

[65] Beheary M G E, Ibrahim I A E, Sanad S A, et al. Impact of Dying Cotton Fibers before Spinning on The Resulting Yarn Mechanical Properties. Journal of the Advances in Agricultural Researches. 2024; 29(4): 618-625. doi: 10.21608/jalexu.2024.321614.1228

[66] Hawlader M R, Siddiky M R H, Uddin A J. From waste to wear: ANN-driven optimization of 100% sustainable tri-blend yarns from recycled cotton, recycled PET, and ecovero. Sustainable Futures. 2026; 11: 101652. doi: 10.1016/j.sftr.2026.101652

[67] Gupta V, Gupta S. Cotton Fiber and Its Sustainable Alternatives. In: Muthu S S, ed. Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry. Sustainable Textiles: Production, Processing, Manufacturing & Chemistry. Springer, Cham. 2023. doi: 10.1007/978-3-031-37323-7_7