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Article

The Quality of Blended Cotton and Denim Waste Fibres: The Effect of Blend Ratio and Waste Category

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Abstract: Cotton is one of the most-used natural fibres in the world due to its relative comfort and strength compared with other natural fibres. However, the processing of cotton for manufacturing products consumes a lot of water, while harvesting cotton uses significant amounts of pesticides. One solution to this ecological problem is to recycle cotton waste. This study investigated the effect of blending virgin cotton with two categories of denim cotton waste—sourced during the winding and dyeing processes and used in various ratios—on the quality of blended denim cotton. The study was realised in collaboration with a large manufacturer of denim fabrics in Tunisia and a producer of preparation machines in Italy and aimed to use an adequate process to recycle cotton yarn waste and to obtain fibres with acceptable quality. The research aimed at providing a solution to the great demand for denim with the use of reclaimed fabric, which accompanies the increased need for denim with a fancy effect and the obligation of denim producers to follow environmental standards required by many brands The results show that it is possible to obtain a good quality of blend yarn using virgin cotton and cotton waste even when the waste content exceeds 50%. These results are significant for textile mills. Reprocessing fibres from denim colour-processing waste has a lot of advantages, including reductions in wastewater treatment and the consumption of energy, chemicals and water. In addition, the process eliminates the need for the dyeing and finishing processes of these coloured fibres.

Keywords: denim; dyed cotton waste; mechanical recycling; fibre quality index; fibre blend

Citation: Kanan, M.; Wannassi, B.; Barham, A.S.; Ben Hassen, M.; Assaf, R. The Quality of Blended Cotton and Denim Waste Fibres: The Effect of Blend Ratio and Waste Category. *Fibers* **2022**, *10*, 76. https://doi.org/10.3390/fib10090076

Academic Editors: Marina Zoccola and Alessia Patrucco

Received: 24 July 2022
Accepted: 29 August 2022
Published: 2 September 2022

1. Introduction

With an annual consumption of approximately 26 million tonnes [1], cotton is one of the fibres used most frequently by the textile industry, particularly in the clothing sector [2]. However, cotton cultivation causes serious ecological and economic problems because it consumes high volumes of water and uses significant amounts of pesticides.

The production of ecologic cotton—an alternative material developed to resolve these problems—involves low water consumption and no pesticides. However, high production costs result in increased yarn prices as cotton represents more than 50% of the yarn's final cost. In addition, the ecologic cotton's quality is lower than that of classic cotton [3].

Recycling cotton is another solution to these problems. The spinning mill, weaving and clothing industries generate a significant amount of waste fibre, yarn and cotton fabric [4].

It was demonstrated that cotton waste can be added as a reinforcement to produce composites [5–7]. Temmink [6] proved that cotton waste can be added to bioresins to obtain a biocomposite for structural applications with high performance. Composites reinforced with cotton waste can be used in many applications, for example, in packaging [8].

In optimal conditions, acceptable mechanical properties of composites are obtained [9–11]. Petruci [9] revealed that 16% of short cotton waste fibres can be added to the polypropylene matrix using the injection moulding process. The obtained composite can resist up to 5000 cycles of fatigue stress under 70% composite tensile strength.

Waste cotton can be utilised to produce drylaid nonwovens [12–14]. Needle punching and the chemical bonding method can be adapted to bond the nonwoven structure. Abidi [14] developed a needle punching nonwoven fabric from cotton waste to be used as biodegradable mulch in agriculture to replace synthetic mulch.

Cotton waste can also be integrated into building materials [15–17]. Algin [16] used cotton wastes and limestone powder wastes to produce a composite as a building material. The results proved that the obtained material has acceptable mechanical and physical properties and higher smoother surface area than conventional bricks available on the market.

Due to its specific properties, cotton waste demonstrated high adsorption capacity for the removal of heavy metals and dyes from wastewater. Researchers demonstrated that this solution is economically very efficient, and a high rate of removal capacity is obtained [18–20].

Wanassi [20] utilised cotton waste to elaborate an activated carbon through carbonisation using zinc chloride chemical activation. It was proven that the obtained material permits high removal of anionic dye from textile wastewater with low cost.

Additionally, some alternatives have been applied to the use of cotton waste for functional application instead of becoming disposal material. Recently, many research works have been focused on the extraction, characterisation and application of nanocellulose crystals from cotton waste in composite films [21–23].

Wang [22] extracted cellulose nanocrystals from cotton waste cloth fabric; the obtained material was used as filler for the reinforcement of the PLA matrix to produce a composite film. The results proved that the addition of 0.1 to 0.3% nanocrystals improves the mechanical properties of the film.

All of the above applications are applied in large part at the laboratory scale. The most important industrial application of cotton waste is the reintegration of the material on the spinning mill. Due to the high variation in the lengths of obtained fibres, the open-end process is more adapted to produce cotton waste yarn than the conventional ring-spinning process [24–26].

Due to the increased demand for fashion garments, denim is one of the most-used materials globally. However, its production harms the environment by using a lot of water and many chemicals [27–29]. Halimi et al. [30,31] developed recycled, open-end yarns from denim production fibre wastage. They demonstrated, using experimental design techniques, that acceptable yarn quality could be obtained using up to 30% recycled fibres. The percentage is low because the recycled fibres used are collected during the preparation and carding processes when the fibres' average length is short.

Currently, great demand is noted for denim with reclaimed fabric, which accompanies the increased need for denim with a fancy effect and the obligation of denim producers to follow the environment standards required by many brands [29]. The main problem in recycling denim cloth and yarns is the existing fraying process.

Classical tearing machines are composed of many rollers with rigid cloth. The fraying process has a negative effect on the mechanical and physical properties of obtained fibres. This limits the possibility of adding a high level of recycled fibres in the spinning process [32,33].

In this research work, realised in collaboration with a large producer of denim fabric in Tunisia, we evaluated the effect of blending two kinds of virgin cotton with two categories of denim cotton waste—sourced during the winding and dyeing processes—on the quality of blended denim cotton.

We used in our study a specific process to recycle textile yarn different from the use of a classical fraying machine to minimise the constraints applied to fibres and to improve their qualities. This process, classically used to recycle nonwoven fabric, was developed to recycle yarn waste in collaboration between denim manufacturers and a producer of preparation fibre machines in Italy.

To evaluate the quality of each fibre blend, a fibre quality index (FQI) was utilised to evaluate the technical value of the blend cotton obtained. Composite yarn quality was also compared to validate our results.

Our research work also presents a positive ecological impact, and in fact, reprocessing fibres from the denim dyeing process has several advantages:

- Energy, chemical and water consumption and the need for wastewater treatment are all reduced.
- The dyeing and finishing processes are eliminated for these coloured fibres.

However, the preparation, dyeing and finishing processes decrease recycled fibre quality.

2. Materials and Methods

2.1. Waste Fibre Preparation

This study investigated two categories of waste denim fibres:

- Waste 1 (W1): white yarn waste from the winding process;
- Waste 2 (W2): blue yarn waste from the dyeing process.

An AMP7 DELL'ORCO machine was used, under optimal conditions [20], to recycle W1 and W2. This machine was adapted to recycle waste yarn gradually without altering its properties. The device comprises a large breaker, and six workers processed the waste fibres gradually without degrading their properties.

2.2. Simulation of the Blending Process

The virgin and waste fibres used in each blend in varying proportions were extracted from laboratory samples obtained according to the sampling method NFG 07-062 as a simulation of the blending process. USTER, AFIS and HVI instruments were used to determine the quality of the virgin and cotton waste fibres by measuring the Nep Count (Neps), Mean Length (ML), Short-Fibre Content (SFC), Linear Density (LD) and Strength (St).

AFIS is based on single-fibre testing. AFIS provides several length parameters derived from individual fibre measurements. Key metrics include: average length, CV% length and percentage of short fibres (defined as the percentage of fibres less than 12.7 mm in length). Fibre length information is provided by weighting fibre length by count or weight. The weight-weighted length distribution is determined by calculating the fibre frequency in the different length intervals, which is the proportion of the total fibre weight in a given length category. The number-weighted length distribution is obtained by calculating the total number of fibres in the different length intervals.

The cotton fibre length weighting by weight or count is calculated from the two distributions accordingly. Once the appropriate AFIS module determines the length distribution, the machine calculates the length distribution by weight, assuming that all fibres have the same fineness. The samples require no preparation, and the result is obtained in 2 to 3 min.

The high-volume instrument (HVI) allows the analysis of 60 to 80 cotton samples per hour. It allows the reading of sample references by barcode, the analysis of Micronaire via a light module, the measurement of length, tenacity and elongation, and finally the determination of colour (grade) and the waste rate.

The length of the fibres is measured by the HVI optically by a light source when the cotton beard is in the fixed clamp. The variations in the light intensity that crosses the beard of fibres are translated into a curve: the lengths and length uniformity are derived from the interpretation of this curve.

2.3. The Yarn Manufacturing Process and Quality Characterisation

Denim yarns (yarn count 92, text and yarn twist 160) were manufactured using a Schlafhorst Autocoro rotor spinning machine's open-end process.

Recycled fibres were blended with Malian cotton with three blending proportions (60%, 80% and 100%). All the proportions used were measured by weight.

The mechanical properties of the yarns were determined with a USTER Tensojet device according to ASTMD76 standards. The characteristics of the test are that the test specimen length is 500 mm, initial tension to be applied is 0.5 +/− 0.1 cN/Tex and test speed is 50–500 mm/min following the elongation at break.

Yarn unevenness was measured using a USTER Tester 5-5800 instrument according to ASTMD6197 standards. The measuring principle is based on an optical system. The thread moves through an optical field comprising two parallel beams of light which illuminate the thread on both sides. The two light beams make an angle of 90 degrees. With this method, it is possible to determine precise results with respect to the diameter, the diameter variation and the surface structure of the wires.

3. Results

3.1. The Quality of the Fibres and Their Blend

The fibre properties are listed in Table 1.

Table 1. Fibre properties.

Fibre	Neps (Cnt/g)	ML (mm)	SFC (%)	LD (mTex)	St (cN/Tex)
Virgin Malian (V1)	66	26.1	6.2	151	30.2
Virgin Greek (V2)	105	25	6.8	163	28.8
Waste 1 (W1)	189	19.6	20.6	146	26.3
Waste 2 (W2)	211	19	21.5	159	25.7

To estimate the quality of cotton, many parameters were measured. It was proven that the most important parameters that affect the quality of cotton yarn are:

- The length of the fibres. The greater the length, the greater the regularity, and the mechanical properties of the yarn are better.
- The tenacity of the fibres. When the tenacity of fibres increases, the mechanical properties of the yarns also increase.
- The fineness of fibres. Fine cotton fibres lead to a high quality of yarn (fineness decreases).

To evaluate the technology value of cotton (give a global quality of cotton to simulate the quality of yarn to be obtained) before spinning, many fibre quality indexes were proposed in the literature [34–36], and some of them are complex. Wannassi proposed a simple quality index and proved a good correlation with yarn quality.

The FQI can be defined by the following formula [37]:

$$\mathrm{FQI} = \frac{\mathrm{ML}\ \times\ \mathrm{Str}}{\mathrm{Fineness}}$$

ML is the mean length in mm, Str is the tenacity in cN/Tex and fineness is expressed in mTex. The FQI of the various virgin (V1: Malian fibre and V2 Greek fibres) and cotton waste blends for the two categories is shown in Tables 2–5, where x is the proportion of blend expressed by weight.

Table 2. FQI for the V1 and W1 blend.

x	Str (cN/Tex)	ML (mm)	Fineness (mTex)	FQI (m $\times$ cN/Tex^2)
0.00	30.20	26.00	151.00	5.20
0.10	29.92	25.23	150.30	5.02
0.20	29.46	24.30	149.60	4.79
0.30	29.10	23.58	149.10	4.60
0.40	28.71	23.10	148.70	4.46
0.50	28.45	22.28	148.20	4.28
0.60	27.83	21.90	147.70	4.13
0.70	27.29	21.02	147.10	3.90
0.80	26.92	20.38	146.70	3.74
0.90	26.47	19.90	146.40	3.60
1.00	26.30	19.60	146.00	3.53

Table 3. FQI for the V1 and W2 blend.

x	Str (cN/Tex)	ML (mm)	Fineness (mTex)	FQI (m × cN/Tex^2)
0.00	30.20	26.00	151.00	5.20
0.10	29.86	25.05	151.80	4.93
0.20	29.52	24.05	152.90	4.64
0.30	29.00	23.79	153.80	4.49
0.40	28.70	22.97	154.80	4.26
0.50	28.10	21.78	155.60	3.93
0.60	27.50	21.01	156.40	3.69
0.70	26.92	20.91	156.80	3.59
0.80	26.60	20.27	157.80	3.42
0.90	26.21	19.69	158.50	3.26
1.00	25.70	19.00	159.00	3.07

Table 4. FQI for the V2 and W1 blend.

x	Str (cN/Tex)	ML (mm)	Fineness (mTex)	FQI (m × cN/Tex^2)
0.00	28.80	25.00	163.00	4.47
0.10	28.62	24.16	160.80	4.30
0.20	28.31	24.02	158.60	4.29
0.30	28.16	22.81	156.50	4.10
0.40	27.98	22.31	154.50	4.04
0.50	27.71	21.77	153.10	3.94
0.60	27.45	21.35	151.30	3.87
0.70	27.13	20.94	149.80	3.79
0.80	26.75	20.49	148.40	3.69
0.90	26.57	19.94	147.40	3.59
1.00	26.30	19.60	146.00	3.53

Table 5. FQI for the V2 and W2 blend.

x	Str (cN/Tex)	ML (mm)	Fineness (mTex)	FQI (m × cN/Tex^2)
0.00	28.80	25.00	161.00	4.47
0.10	28.50	24.28	162.40	4.26
0.20	28.30	23.41	162.10	4.09
0.30	27.92	22.88	161.50	3.96
0.40	27.71	22.18	161.20	3.81
0.50	27.30	21.89	160.70	3.72
0.60	27.01	20.88	160.40	3.52
0.70	26.51	20.55	159.90	3.41
0.80	26.13	19.87	159.60	3.25
0.90	26.00	19.47	159.30	3.18
1.00	25.70	19.00	159.00	3.07

As a first statistical analysis, a one-way ANOVA test for FQI for all the blends was performed. The results are represented in Figure 1.

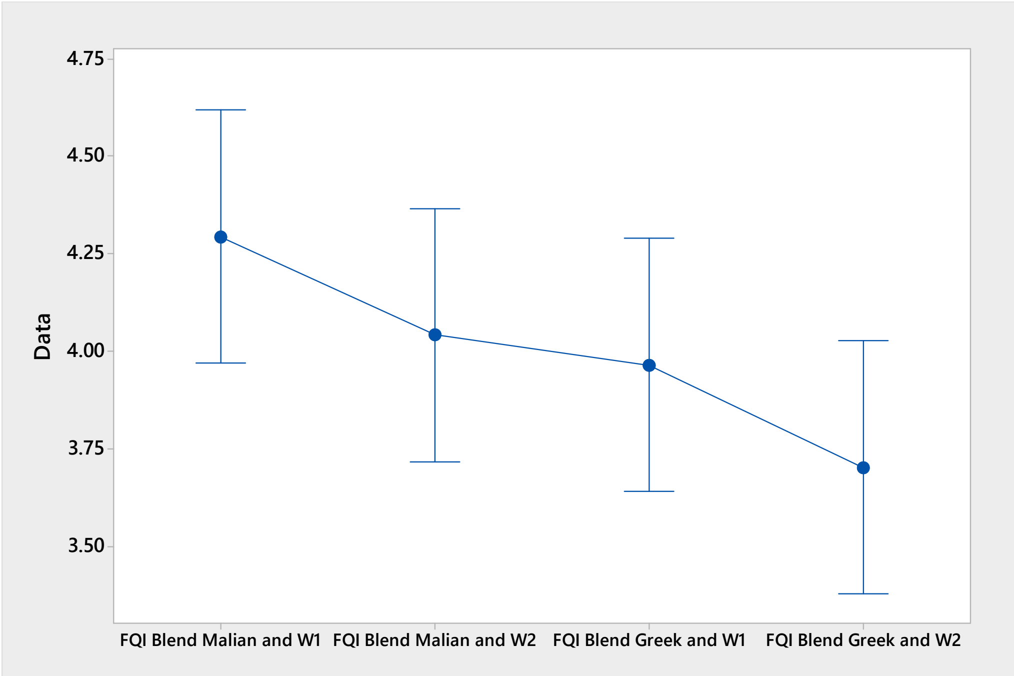

Figure 1. Variation in FQI for different blends.

In the hypothesis test, whether there is a significant variation in FQI between all the blends with a risk of 5% was tested. The p value obtained was 0.092.

The hypothesis H should be rejected. Statistically, there is no significant difference between the FQI for all the blends. To perform a physical analysis of the phenomena, all the FQI for blends will be analysed according to their variation.

The results in Tables 2 and 3 indicate that when blended with V1, increasing the percentage content of W1 from 0% to 50% causes a 21% drop in FQI. The variation is around 32% when W2 wastes with the same ratio were used.

The V2 blend results, shown in Tables 4 and 5, indicate that the FQI variation is between 13% and 26% when the percentage content of W1 is 50% and 26% when blended with W2 with the same percentage content. The variations in FQI between the virgin fibres can be explained by the variation in the length of recycled fibres and the degradation of their mechanical properties.

During manufacture, fibres are stressed by the spinning and winding processes, which decrease their strength and length. There is more degradation with W2 fibres because they are collected from a more advanced stage than the W1 fibres.

Figure 2 represents a deeper analysis by presenting only the FQI results. The data show that increased waste fibre content decreases the FQI for the V1 and V2 fibres. At the same content ratio, using W1 results in a better-quality blend than using W2. The FQI is better for V1 (better length and finesses parameters) than with V2 fibres.

x = 0.3 (Figure 2) is used as a reference point as, according to previous studies in recycling cotton waste, this was the maximum recommended rate as, beyond this, the quality of recycled yarn decreases [19].

It is noteworthy that:

- Blending 60% W1 with 40% V1 fibres obtains the same FQI as when 30% W1 and 70% V2 fibres are blended.
- Blending 50% W2 with 50% V1 fibres obtains the same FQI as when 30% W2 and 70% V2 fibres are blended.

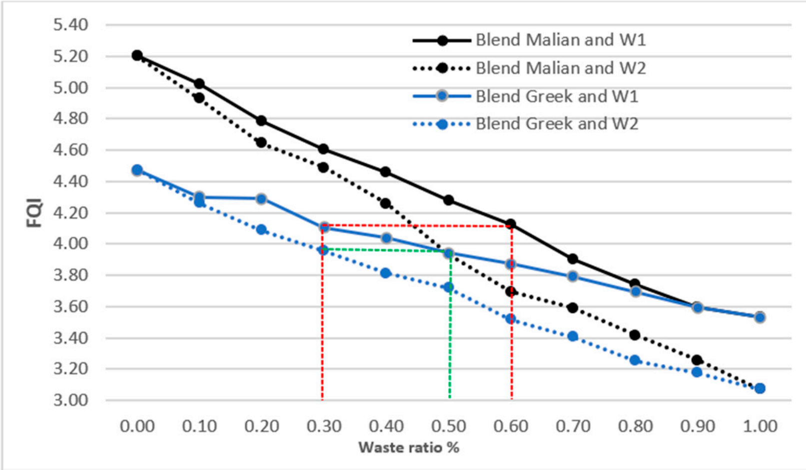

Figure 2. The effect of waste cotton proportion on the blends' FQI.

It can be concluded that it is possible to obtain an acceptable blend quality even when using dyed fibres with a higher percentage of waste fibres when the following two conditions are satisfied:

- An appropriate fibre separation process is used (because classical tearing machines are better used with garment waste than yarn waste);
- Suitable-quality fibres are used (V1 fibre length in this case).

3.2. The Quality of the Blended Yarns

The quality of the yarns obtained from the W1 and W2 is shown in Tables 6 and 7, where Cvm (%) = the irregularity of the yarn expressed as a percentage, Thin (−30%) = the number of thin defects on the yarn with a section less than 30%, Thick (+30%) = the number of thick defects on the yarn with a section more than 30%, Ten (cN/Tex) = tenacity of the yarn expressed as cN/Tex and El (%) = elongation of the yarn as a percentage.

Table 6. The quality of blended yarn (W1 and V1 blend).

Waste (%)	CVm (%)	Thin (−30%)	Thick (+30%)	Ten (cN/Tex)	El (%)
0	10.8	481	240	15.48	7.98
60	12.61	812	345	10.45	6.74
80	19.34	883	351	9.64	6.66
100	23.04	889	360	9.31	6.38

Table 7. The quality of blended yarn (W2 and V1 blend).

Waste (%)	CVm (%)	Thin (−30%)	Thick (+30%)	Ten (cN/Tex)	El (%)
0	10.8	481	240	15.48	7.98
60	13.74	1037	234	8.84	6.82
80	15.97	1139	258	8.64	5.56
100	25.22	1288	577	7.53	5.18

To conduct a first statistical analysis of the hypothesis of the difference in the final parameters, a one-way ANOVA test for the different properties of yarns for the two blends was performed.

The results are presented in Table 8. It can be confirmed that, statistically, the hypothesis that there is no difference between properties of yarns for the two blends with a risk of 5% can be accepted.

Table 8. One-way ANOVA test for yarn properties of blends.

Yarn Properties	CVm (%)	Thin	Thick	Ten	El
Pvalue	0.997	0.316	0.972	0.652	0.475

The data in Tables 6 and 7 show that:

- The regularity of the yarn decreases (while the Cvm, Thin and Thick of the yarn increase) when the proportion of waste cotton that is used increases. Waste fibres contain more short fibres, which causes more perturbation in the drafting zone of the ring frame machine, creating imperfections and defects.
- The mechanical properties of the yarns decrease with increased waste fibre content. The yarns' mechanical properties correlate to the fibres' mechanical properties. During the manufacturing and recycling processes, many mechanical forces are exerted on the recycled fibres, which lose a part of their mechanical properties.

To compare the quality of the yarns for the W1 and W2 blends, Figures 3–5 show the effect of the most critical yarn properties (Cvm (%), El (%) and Ten (cN/Tex)).

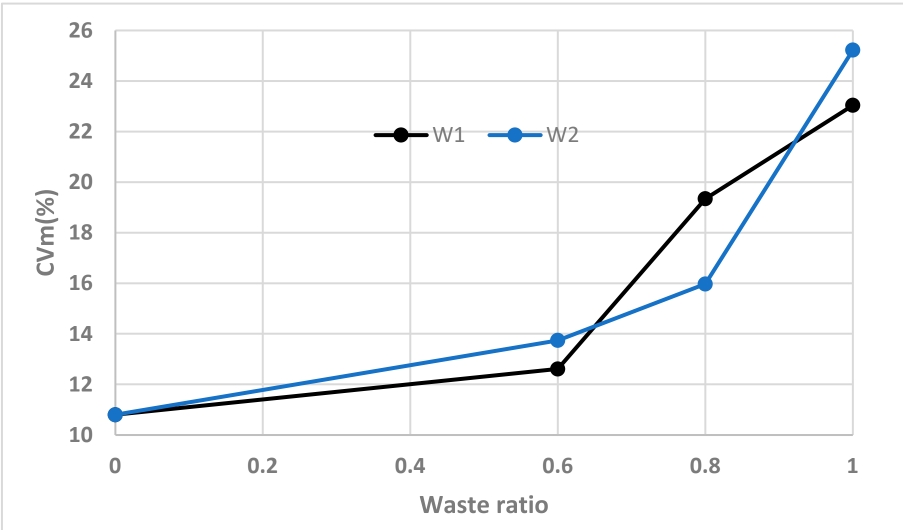

Figure 3. The effect of the proportion of waste fibre content on the irregularity of blended yarns.

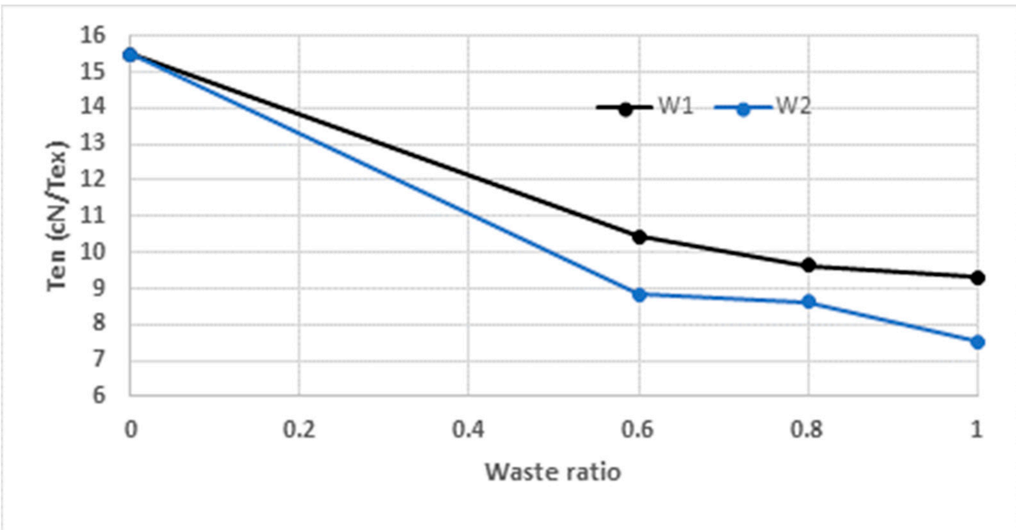

Figure 4. The effect of the proportion of waste fibre content on the tenacity of blended yarns.

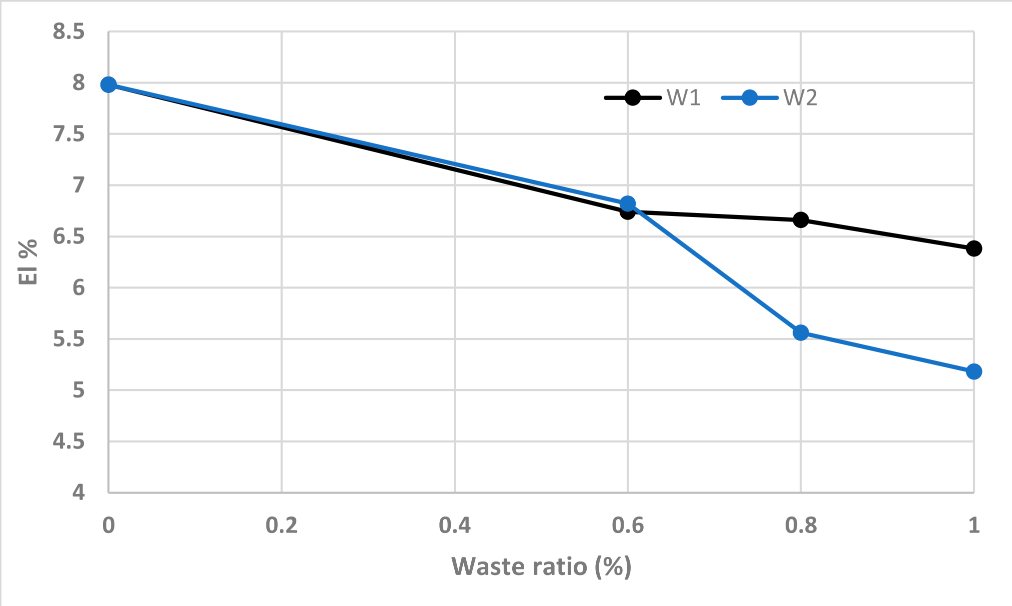

Figure 5. The effect of the proportion of waste fibre content on the elongation of blended yarns.

The results confirm that, globally, the quality of blended yarns using W1 waste is better than the quality of those using W2 waste. The quality of the yarns correlates to the quality of the fibres created. The data demonstrate that W2 waste fibres are more stressed than W1 waste fibres with better quality. It is interesting to note the variation in quality between the yarns, with both types being suitable for a waste fibre content of up to 60%.

When analysed, the irregularity (Cvm (%)) of W1-blended yarns increases by 16.7% when the proportion of waste fibres used ranges from 0% to 60%. It increases by approximately 53% when the proportion of waste fibres used ranges from 60% to 80%. For W1- and W2-blended yarns, it can be confirmed that a maximum of 60% of waste fibres can be used in the blend, as when this proportion is exceeded, a significant increase in yarn irregularity occurs.

For the mechanical properties of yarns, with W1-fibre-blended yarns, the tenacity of the yarn decreases by 32% when 0% to 60% waste fibres are used, and there is a decrease in elongation of 15%. This degradation becomes less critical when the waste fibre content is between 60% and 80%.

These mechanical property variations are acceptable in denim manufacturing processes. Denim yarns pass through a sizing process, which increases their mechanical performance.

On the other hand, a high increase in yarn irregularities is more critical, as imperfections can negatively affect the yield of the winding, warping and weaving processes and can increase the number of defects in the final denim product.

4. Conclusions

This study investigated the effect of blending virgin cotton and two types of denim cotton waste, obtained during the winding and dyeing processes and used at different ratios, on the quality of the fibre and yarn blends. It can be concluded that a high-quality composite can be produced using dyed fibres. With a high waste ratio, when the two conditions are satisfied, the process for fibre separation is suitable, and the fibres used are of appropriate quality. Blends are made with fibres of acceptable quality (V1 fibre length in this case).

The quality of yarn results confirm that a blend using 60% waste fibres with no sign of degradation in the quality of blended yarns can be utilised.

The results are of significant importance to textile mills. Reprocessing fibres from denim dyeing wastage has many advantages, including reductions in wastewater treatment and energy, and chemical and water consumption. In addition, the process eliminates the need for the dyeing and finishing processes for these coloured fibres.

Author Contributions: Conceptualization, M.K., B.W., A.S.B., M.B.H. and R.A.; Methodology, M.K., B.W., A.S.B., M.B.H. and R.A.; Validation, M.K., B.W., A.S.B., M.B.H. and R.A.; Data curation, M.K., B.W., A.S.B., M.B.H. and R.A.; Supervision, M.K., M.B.H.; Validation, M.K., M.B.H.; Writing—original draft, M.K., M.B.H.; Writing—review & editing, M.K., M.B.H., A.S.B., R.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

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