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Production of Sustainable Yarn Incorporating Process Waste to Promote Sustainability

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Abstract: The spinning industry makes a major contribution to environmental pollution due to the excessive use of natural assets and the generation of remarkable amounts of waste during manufacturing processes. Now, the spinning industries are concentrating on sustainable activities due to environmental issues. While textile recycling efforts have been widely explored, the utilization of soft waste (process waste) in yarn production remains underexplored. This study addresses this gap by investigating a sustainable approach incorporating soft waste into producing sustainable yarn using the ring-spinning technique. The research explores the properties of yarns manufactured from a blend of virgin cotton and soft waste, and 100% virgin cotton yarn is produced for comparison. The results indicate that incorporating soft waste leads to an increase in CVm% (13 vs. 11), hairiness (6.9 vs. 5.1), and IPI (165 vs. 125) compared to virgin cotton yarn. However, the elongation percentage (7.1% vs. 8%) and tensile strength (12.6 cN/tex vs. 16.2 cN/tex) showed a reduction, highlighting potential trade-offs in mechanical properties. The statistical analysis applies one-way ANOVA to evaluate the significance of variations in yarn characteristics made from the mixture of soft waste + virgin cotton and only virgin cotton. The manufactured yarns were examined in a modern weaving machine as weft yarn for fabric (denim) manufacturing and found to be perfect for normal operation. The article focuses on reducing negative impacts on the fabric (denim) manufacturing environment by incorporating soft waste to produce sustainable yarn. This research provides important insights into the production of sustainable yarns, focusing on environmental concerns.

Keywords: sustainable production; process waste; ring-spun yarn; environmental concerns; yarn characteristics

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Academic Editors: Ángeles Blanco and Andrea Petrella

Received: 21 January 2025
Revised: 27 February 2025
Accepted: 5 March 2025
Published: 6 March 2025

Citation: Hamzi, A.; Habib, A.; Babaarslan, O.; Abushaega, M.M.; Masum, M.; al Mamun, M.A. Production of Sustainable Yarn Incorporating Process Waste to Promote Sustainability. *Processes* **2025**, *13*, 764. https://doi.org/10.3390/pr13030764

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1. Introduction

Over the last few years, growing environmental awareness has become a global issue, prompting the textile and garments industry to move towards more sustainable practices. The garments business has recently been considered the most harmful business in the economy due to environmental issues [1]. Garments and textile companies are now facing a tough situation regarding these maintained or increasing levels of waste. These wastes become a burden in landfills and harm the environment. The need for textiles and clothing in daily life is important for survival and has a huge environmental impact including

air pollution, soil degradation, and water pollution [2,3]. Most of these wastes (textiles) are thrown into the environment, and only a small amount is reused and recycled [4], which creates greenhouse gases and has harmful impacts on the living organisms of the environment [5].

The rapid growth and increased production of textile companies resulted in a greater output of fiber (cotton) waste. The larger portion of cotton waste can be observed everywhere around the globe [6]. Spinning industries have been assisted by utilizing (reusing) and recycling facilities for active waste management to reduce their bad influence on the environment [7]. However, cotton fiber is the most utilized fiber all over the world and to cultivate this fiber, a huge number of natural resources have been consumed, along with water [8]. A huge amount of water is necessary to cultivate cotton fiber, which has alarming consequences for nature. The circular economy encourages the utilization of textile waste and sustainable waste disposal activities to provide benefits to the environment by transforming waste (textile) into value-added textile items [6,9–11]. About 85% of manufacturing waste worldwide is assumed to ultimately end up in landfills [12–14]. This condition can be altered if textile components are given a circular position in the chain of production and utilization through their recycling and reuse [15].

Azad et al. (2024) highlight the significant advancements in recycling practices within the textile sector, detailing how pre-consumer waste is converted into recycled fibers and yarns. Their work underscores the necessity of understanding the sustainable manufacturing practices, which can lead to a reduction in resource consumption and improved waste management strategies in the industry [16]. Aishwariya (2020) discussed the negative impacts of textile waste on the environment and focused on proper waste management methods with a more positive environmental impact [17].

Uddin and Roy (2024) introduce an innovative strategy for transforming mélange fabric waste into mélange yarns using compact spinning techniques. Their research advocates the use of cleaner production methods, demonstrating how existing waste can be integrated into new yarn manufacturing processes to promote sustainability [18]. The integration of lean management principles into textile production, as discussed by Abedin and Siddique (2024), presents a complementary approach to waste management. By streamlining production processes, manufacturers can enhance resource efficiency and minimize waste generation [19]. Uddin and Rahman (2024) explored the sustainable production of hybrid yarns for denim, maximizing the use of recycled cotton derived from fabric waste. Their findings highlight the potential of recycled fibers to enhance elasticity and resilience while maintaining a high-quality denim performance. This study found that the use of 70% recycled cotton with 30% virgin cotton is unsuitable for ring yarn production due to its high roving breakage, while a mix of 60% recycled and 40% virgin cotton results in lower-quality yarn than other yarn types [20]. Njeru (2023) further supports the use of sustainable design principles in waste management, advocating for a circular economy approach that prioritizes upcycling and waste minimization. The notion of "production with zero waste" is particularly relevant in the context of mélange yarn production, where integrating waste materials can significantly reduce environmental impact [21].

Manocha and Dharwal (2023) discuss the role of sustainable fashion businesses in promoting the use of biodegradable and recycled materials [22]. Arafat and Uddin (2022) investigated the incorporation of recycled fiber from textile waste in ring-spinning to produce yarns. Their study emphasized the environmental and economic benefits of using recycled fibers, aligning with the growing demand for sustainable and eco-friendly textile manufacturing. These studies collectively reinforce the feasibility of integrating recycled fibers into yarn production without compromising quality, offering a pathway toward more sustainable denim manufacturing [23].

Despite the growing body of research on sustainable practices in textile production, there remains a significant gap in understanding the specific effects of integrating soft waste on yarn characteristics and overall production efficiency. Most studies focused on broader recycling strategies without deeply exploring the mechanical implications of varying waste percentages in yarn manufacturing. This study seeks to address this gap by systematically analyzing the influence of process waste on yarn properties. The study will also examine the properties of yarn made from process waste and virgin cotton and assess its suitability for denim fabric production.

2. Materials and Methodology

In this research, Ne 16/1 carded yarn was produced using two types of cotton fiber: process waste and 100% virgin cotton. The 100% cotton fibers were sourced from local suppliers and process wastes (soft wastes) were collected from the spinning section. The characteristics of 100% Indian cotton (virgin) and waste collected from the spinning line are expressed in Tables 1 and 2, respectively, which were tested using AFIS (Advanced Fiber Information System) and Uster HVI 1000 equipment (Uster Technologies AG, Uster, Switzerland). These analyses provided critical insights into fiber length, fineness, strength, and neps content, ensuring an accurate assessment of the impact of process waste on yarn properties. According to the test results, the properties of the fiber made using process waste were not bad and it can be used to produce yarn when mixed with virgin cotton.

To produce the yarn, a blend of 50% cotton (process waste) and 50% virgin cotton was used and the required amount of cotton fiber was weighted, utilizing an electrical balance. Then, fibers (50:50) were blended manually and left at the desired temperature for conditioning for eight hours. To produce the desired quantity of yarn, 50 kg of fibers were weighed before laydown to obtain 20 roving fibers, each weighing between 1.25 kg and 1.5 kg. After conditioning, the fiber blends were processed through the blowroom, carding machine, first and second draw frames, and roving frames. The produced roving was then fed into the ring-spinning frame to produce the desired yarn. The specifications of the different machines are shown in Table 3.

The properties of the yarn were examined and 100% cotton (virgin) carded yarn was integrated for comparison. Forty test results were obtained for each yarn property, and the calculated average values were used for investigation. The CVm% (coefficient of mass variation), hairiness (H), and its variation (sH), along with the imperfection index (including thick places, neps, and thin places), were measured using the Uster® Tester 4 (UT 4, Uster Technology, Uster, Switzerland), following the standards ISO 16549:2021 [24]. Yarn strength and elongation were assessed using the Uster Tensorapid-3, adhering to the TS EN ISO 2062:2009 standards [25]. Microscopic images of individual yarns were captured using a Trinocular Light Microscope (TLM) manufactured by KRÜSS (Hamburg, Germany). The developed yarn was tested for use as weft in denim fabric production using an air-jet weaving machine.

Table 1. Characteristics of cotton (virgin) and process waste (AFIS).

Materials	Fiber Neps Size (μm)	Fiber Neps/g	Seed-Coat Neps Size (μm)	Seed-Coat Neps/g	Short-Fiber Contents (w) % (<12.7 mm)	Upper Quartile Length (n), mm	Short-Fiber Contents (w) % (<12.7 mm)	Fineness (mtex)
Cotton (virgin) fiber	680	189	1089	7	6.50	27.00	6.20	156
Blowroom waste (dropping-2)	736	1126	1118	111	88.10	11.40	74.60	152
Carding waste (dropping-1)	724	391	1184	119	34.30	26.00	12.90	154
Carding waste (flat strip waste)	672	719	1031	239	52.80	25.60	22.90	152
Comber waste (Noil)	629	527	892	115	81.50	11.70	65.40	153
Ring frame waste (Pneumafil)	616	188	685	3	40.90	27.30	18.80	151

Table 2. Characteristics of cotton and process waste (Uster HVI 1000 instrument).

Fibers	SCI	Micronaire (μg/inch)	Maturity	Length (mm)	UI (%)	SFI	Strength cN/tex	Elongation (%)	Moisture (%)	Trash Content%
100% cotton (virgin)	138	4.54	0.91	28.97	85.72	7.05	30.49	6.85	7.58	139.20
Dropping-2	22	4.02	0.86	18.15	57.10	90.00	23.70	5.90	6.30	518.00
Dropping-1	69	4.86	0.91	26.18	79.20	26.40	24.70	6.01	5.90	389.00
Flat strip waste	76	4.65	0.89	24.79	76.40	40.90	27.90	5.70	5.60	214.00

Table 3. Parameters of production.

Machine Name	Brand Name	Speed
Blowroom	Rieter-MBO R34	1000 kg/h Chute feed to card
Carding	Rieter C60	145 m/min
1st draw frame	Rieter-SB D-22	6 doubling (650 m/min)
2nd draw frame	Rieter-RSB D-24	6 doubling (650 m/min)
Roving frame	Electrojet-Rovematic AF	Flyer speed of 1000 rpm
Ring frame	Jingwei-F1520m	Spindle speed of 10,000 rpm

In addition, the Yarn Quality Index (YQI) serves as an important parameter for assessing yarn quality. YQI reflects the overall excellence of the yarn. Typically, a higher YQI signifies better yarn quality. The YQI takes into account factors such as elongation, irregularity, and strength. The following formula is used to calculate the YQI [26–28]:

$$\text{YQI} = \text{Elongation\%} \times \text{Yarn tenacity (cN/tex)}/\text{Unevenness\%} \quad (1)$$

The various yarns were statistically analyzed using one-way ANOVA with SPSS 25.0, set at a confidence level of 95.0% (significance level of 0.050). A *p*-value below 0.050 illustrates a statistically significant difference [29]. In this analysis, the null hypothesis (H_0) posits that there is no significant variation in characteristics between yarns manufactured from virgin cotton and those made from process waste, while the alternative hypothesis (H_1) asserts that a significant difference exists between the two.

3. Results and Discussions

3.1. Yarn Strength and Elongation%

The mechanical properties of yarn, particularly strength and elongation, are crucial determinants of its performance in subsequent textile processes such as weaving and knitting [30]. Figure 1 presents the strength (cN/tex) measurements of the yarns produced, highlighting the distinct difference between those containing 50% process waste and those made entirely from 100% virgin cotton. The results indicate that the yarn made with 50% process waste exhibited a lower strength. This reduction in strength can be traced back to the inherent properties of the process waste, which are generally shorter in length compared to the fibers derived from virgin cotton. Shorter fibers have less effective bonding capabilities, leading to weaker inter-fiber connections during the spinning process. Consequently, this results in a reduction in the yarn's overall tensile strength. Furthermore, the increased presence of weaker fibers derived from multiple processing cycles may introduce structural discontinuities, thereby negatively impacting the stress distribution across the yarn body.

The elongation percentages, also illustrated in Figure 1, follow a similar trend. Previous research has demonstrated that fiber length plays a significant role in determining yarn elongation, as longer fibers contribute to better fiber engagement, stronger cohesion, and improved stress distribution throughout the yarn structure [31,32]. Yarn containing 50% process waste demonstrates significantly lower elongation compared to 100% virgin cotton yarn. This reduced elongation can be linked to the presence of shorter fibers in the process waste, which do not effectively integrate with the yarn structure. This inability to bond well leads to a higher likelihood of fiber detachment under tension, thereby compromising the elongation capacity of the yarn. This finding highlights the significant role of fiber length in maintaining the mechanical properties of yarn.

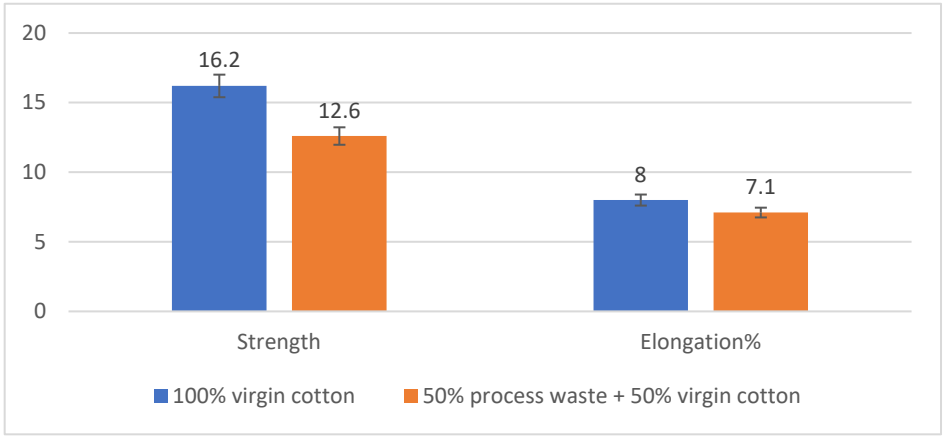


Figure 1. Yarn strength and elongation.

3.2. Yarn Hairiness and Its Variations

Hairiness is a key parameter affecting yarn aesthetics and fabric performance [33]. Figure 2 reveals the hairiness (H) of the yarns along with its variations (sH). It is observed that yarns composed of 50% process waste exhibit higher hairiness values than those made from 100% virgin cotton (Figure 3). This elevated hairiness can be attributed to the shorter lengths of the process waste, which are less controllable during the yarn manufacturing process. These short fibers tend to protrude from the yarn's surface, leading to an increase in overall hairiness [34]. An increased hairiness can negatively affect fabric appearance and performance, making this an important factor to consider in the production of yarn from process waste. The control of the fiber length distribution and the improvements in fiber preparation before spinning must be explored to mitigate excessive hairiness.

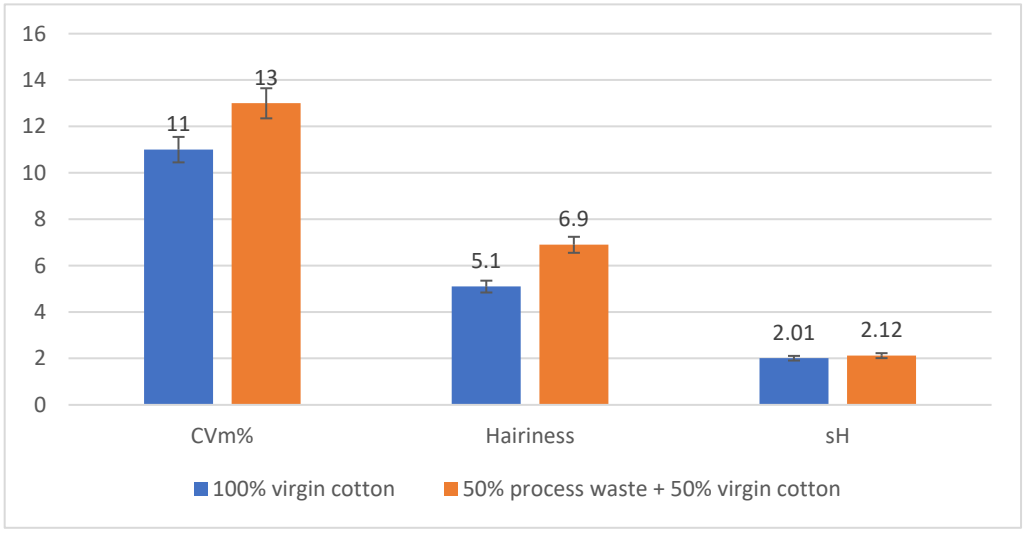
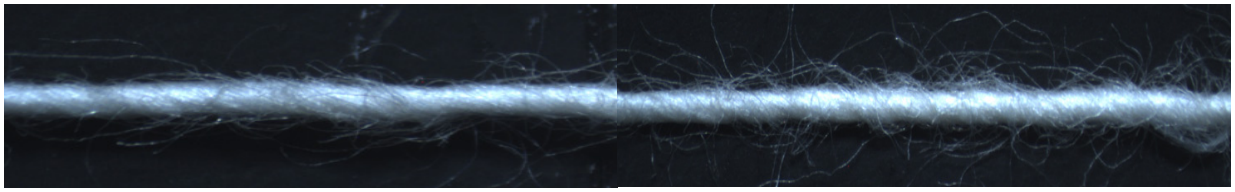


Figure 2. Yarn hairiness and its variations and unevenness (CVm%).



(**a**) (**b**)

Figure 3. Microscopic images of yarns (10×) 100 µm: (**a**) 100% virgin cotton yarn (10×); (**b**) 50% process waste +50% virgin cotton yarn (10×).

3.3. Coefficient of Mass Variation (CVm%)

Unevenness in yarn directly influences fabric quality [35]. As indicated in Figure 2, the coefficient of mass variation (CVm%) is higher for yarns containing 50% process waste than those made from 100% virgin cotton. This higher CVm% reflects the irregularities in mass distribution within the yarn, which can be attributed to the challenges in managing short fibers during the drafting phase of spinning. These fibers contribute to the inconsistent thickness and unevenness in the yarn, leading to undesirable variations in mass. Such irregularities can adversely affect the quality and uniformity of the final textile products, pointing to the need for improved processing techniques. This finding suggests the need for enhanced waste-sorting and fiber-blending techniques to improve uniformity in sustainable yarn production.

3.4. Imperfection Index (IPI) of Yarn

The imperfection index (IPI), which assesses thick places, neps, and thin places, is shown in Figure 4. The results demonstrate that yarns with 50% process waste have a higher IPI compared to those made from 100% virgin cotton. This increased imperfection index highlights the presence of more defects, like thick places, thin places, and neps, in the yarn containing process waste. The process waste's shorter fibers contribute to a greater incidence of these imperfections, which can detrimentally affect the overall yarn quality. Additionally, fibers from process waste often undergo multiple mechanical stresses during their initial use, which can result in increased fiber breakage and a higher generation of unwanted defects such as thick and thin places. A high IPI negatively influences not only the spinnability of the yarn but also its downstream applications in weaving and knitting, potentially causing issues like increased breakage rates and an irregular fabric appearance. Understanding and mitigating these imperfections will be crucial for enhancing the marketability of yarns produced from process waste. To mitigate these defects, process optimization strategies, such as controlled fiber mixing and improved spinning techniques, should be considered.

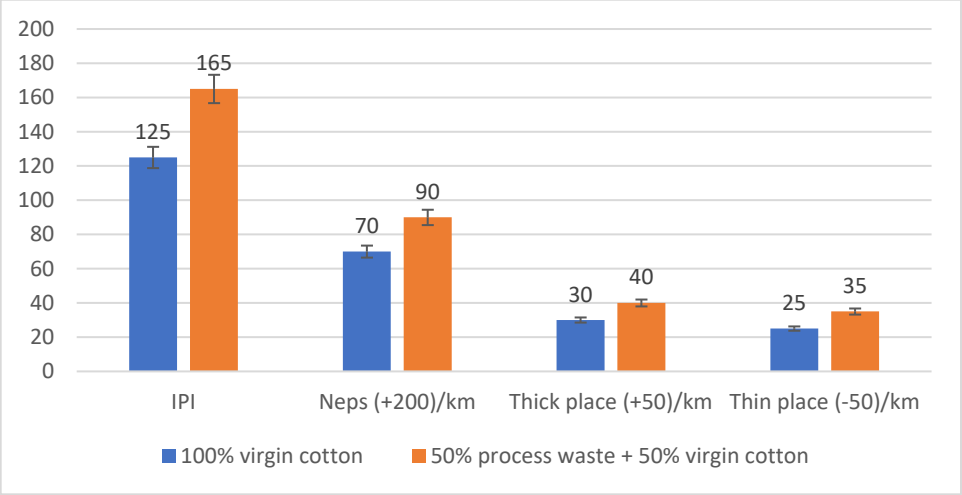


Figure 4. IPI (imperfection index) of yarn, including neps, thick places, and thin places.

3.5. YQI (Yarn Quality Index)

Determining the YQI is necessary for gaining a deeper insight into the yarn's quality [36–38]. Figure 5 presents the YQI of various yarns. Yarn containing 50% process waste demonstrates a significantly lower YQI value compared to 100% virgin cotton yarn because the elongation and strength of the 100% virgin cotton yarn are higher and the unevenness% is lower than those of the yarn containing 50% process waste. The results suggest that while

process waste can be integrated into sustainable yarn production, the further optimization of fiber preparation and spinning parameters is necessary to enhance overall quality.

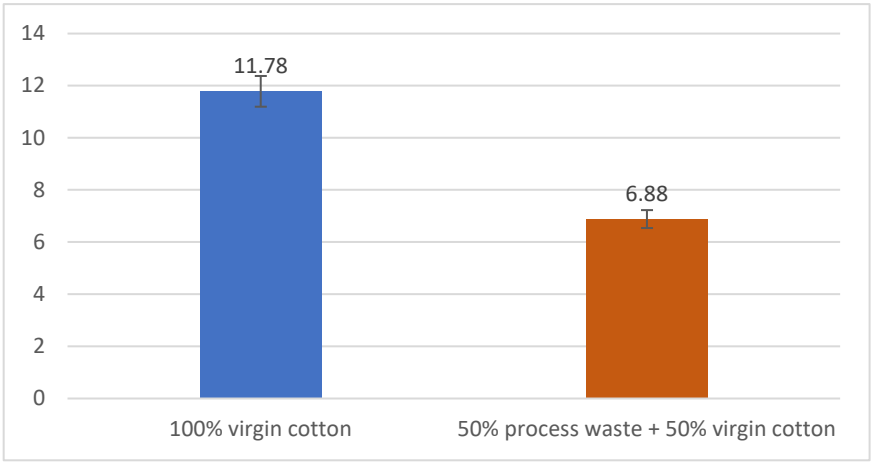


Figure 5. YQI (yarn quality index).

3.6. Statistical Analysis

The statistical evaluation, utilizing one-way ANOVA, reveals that the '*p*' value for all yarn characteristics is below 0.05. This indicates the rejection of the null hypothesis in favor of the alternative hypothesis, suggesting significant differences in the properties of yarns made from virgin cotton compared to those made from process waste. The F-values, presented in Table 4, further substantiate these findings, as they exceed the critical values for each yarn property, reinforcing the presence of significant differences between virgin cotton and process waste yarns. Higher F-values suggest a substantial variance between the two groups, indicating that fiber composition plays a crucial role in determining yarn performance metrics.

Table 4. One-way ANOVA (statistical analysis) for yarn properties.

Variable (Dependent)	F	Sig.
Strength (cN/tex)	42.53	0.001
Unevenness (CVm%)	102.32	0.002
Elongation	31.57	0.000
Hairiness (H)	50.32	0.003
Hairiness variation (sH)	22.01	0.002
Neps (+200)/km	11.20	0.033
Thick place (+50)/km	10.21	0.041
Thin place (−50)/km	18.32	0.040
IPI	16.32	0.039
YQI	15.34	0.029

3.7. Sustainable Approach

Cotton is the most widely used fiber in the manufacturing industry (textile), but its cultivation has remarkable environmental influences, including high water consumption and chemical use [39]. In response to these concerns, this study explores the potential of blending process waste with virgin cotton to produce more sustainable yarn, aligning with global goals for responsible consumption and production. In 2023, global cotton production reached 24.4 million tons, representing 19.9% of the market, while recycled cotton accounted for merely 1% (319,000 tons) [40,41]. Cultivating 1 kg of cotton fiber typically requires between 10,000 to 20,000 L of water and the use of fertilizers and pesticides in cotton

farming poses environmental risks [42,43]. This study employed a blend of fifty percent process waste and fifty percent virgin cotton for yarn production, moving away from the exclusive use of virgin cotton. This method alleviates the environmental burden associated with virgin cotton cultivation. Utilizing process waste also results in less water consumption than traditional methods relying solely on virgin cotton, contributing to Sustainable Development Goal 12 (Responsible Consumption and Production). Integrating process waste presents an innovative, sustainable solution to reduce environmental pressure.

3.8. Fabric (Denim) Production

The integration of the developed yarn into denim fabric production was investigated to assess its performance and potential for sustainable textile manufacturing. The yarn produced was utilized as weft in denim fabric using an air-jet weaving machine (Picanol Ommi Summum, Ypres, Belgium), with Ne 16 indigo-dyed yarn serving as the warp. The denim fabric was constructed in a 3/1 'Z' twill pattern with an EPI of 62 and a PPI of 58. The study found that the yarn produced from the mixture of process waste and virgin cotton performed well during fabric production, operating smoothly at a speed of 700 rpm. Yarn comprising 50% process waste was successfully used as weft, albeit at a slightly reduced speed, marking a significant achievement in this research. Its successful integration into weaving operations suggests its suitability for medium- to heavy-weight textile applications, including denim and upholstery fabrics, where slight variations in yarn quality are more tolerable. However, the increased hairiness and imperfection levels may limit its use in finer, high-performance textile applications requiring superior uniformity and surface smoothness. However, this study does not explore the properties of the fabric. A thorough evaluation of the fabric characteristics is crucial to gaining a comprehensive understanding of both yarn and fabric performance. The properties of the fabric will be discussed in future studies.

4. Conclusions

This research assessed the viability of producing denim yarn using process waste collected from spinning lines. While the yarn with 50% process waste displayed slightly inferior quality to that made from virgin cotton, it remains suitable for denim fabric production. Compared to 100% virgin cotton yarn, the blended yarn exhibited a 22.2% reduction in tensile strength and an 11.3% decrease in elongation percentage. The hairiness (H) increased by 35.3%, the coefficient of mass variation (CVm%) by 18.1%, and the imperfection index (IPI) demonstrated a notable rise of 32%, highlighting the challenges associated with the fiber shortness of the process waste. The results underscore the potential of using process waste as a practical alternative to virgin cotton, emphasizing its environmental benefits. The one-way ANOVA statistical analysis confirmed there were consequential differences in all yarn properties derived from virgin cotton versus process waste. Additionally, the resource savings in cotton production align with the Sustainable Development Goals, particularly SDG-12 (Responsible Consumption and Production). This research emphasizes the environmental benefits of integrating process waste in yarn production, promoting a more sustainable approach.

Further studies should also examine the long-term durability and fabric performance of denim produced from yarns with varying proportions of process waste. Moreover, a life cycle assessment (LCA) of yarns incorporating process waste could quantify the overall environmental benefits, reinforcing the sustainability argument for their broader adoption in the textile industry.

Author Contributions: Conceptualization, A.H. (Ahsan Habib) and O.B.; Methodology, A.H. (Ahsan Habib) and O.B.; Software, M.M.; Validation, O.B. and M.M.; Formal Analysis, A.H. (Ahsan Habib), A.H. (Ahmed Hamzi) and M.M.A.; Investigation, A.H. (Ahmed Hamzi), A.H. (Ahsan Habib), M.M.A., O.B. and M.M.; Resources, A.H. (Ahmed Hamzi), M.M.A., A.H. (Ahsan Habib) and M.A.a.M.; Data Curation, A.H. (Ahsan Habib); Writing—Original Draft Preparation, A.H. (Ahsan Habib); Writing—Review and Editing, A.H. (Ahmed Hamzi), O.B. and M.M.; Visualization, A.H. (Ahmed Hamzi), A.H. (Ahsan Habib), M.M.A. and O.B.; Supervision, O.B. and M.M.; Project Administration, O.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no specific grant from public, commercial, or not-for-profit funding agencies.

Data Availability Statement: The authors confirm that the data supporting this study's findings are available within the article.

Acknowledgments: The authors express their gratitude to Alhaj Karim Textile Ltd. in Manikganj, Bangladesh, for their invaluable support and for facilitating the experimental research conducted in their facilities.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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