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From Waste to Weave: Recycling Industrial and Consumer Cotton Waste for Sustainable and Cost-Effective Terry Fabric Production

Od odpadkov do tkanja: recikliranje industrijskih in potrošniških bombažnih odpadkov za trajnostno in stroškovno učinkovito proizvodnjo frotirja

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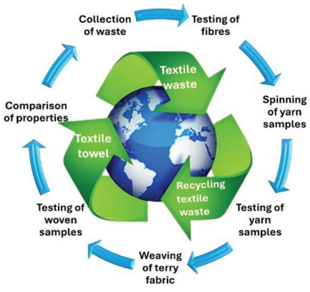
Abstract

The textile sector is a major source of global pollution and resource depletion, generating waste at every stage of production, from spinning to garment manufacturing. This study addresses the critical need for sustainability in the textile industry by exploring the recycling of pre- and post-consumer textile waste to produce terry fabric. This research emphasizes a sustainable approach to recycling, utilizing pre-consumer waste, such as blowroom and carding waste, alongside post-consumer waste from discarded garments. These recycled fibres were spun into yarn and woven into terry fabric, and their properties compared to those of virgin cotton terry. While virgin cotton terry exhibited minor advantages in visual and tactile qualities, other properties remained consistent across all samples. A cost analysis further demonstrated the feasibility of producing medium to high-quality terry fabric from recycled yarn, providing a cost-effective alternative to virgin cotton. The research work contributes to the advancement of sustainable textile production, underscoring the potential of recycling to mitigate the environmental impact of the textile industry.
Keywords: recycling; sustainability; cotton waste; terry fabric; cost-effectiveness

Graphical abstract



Izvleček

Tekstilni sektor je z ustvarjanjem odpadkov na vseh stopnjah proizvodnje, od predenja do izdelave oblačil, velik vir globalnega onesnaževanja in izčrpavanja virov. Ta raziskava obravnava nujno potrebo po trajnosti v tekstilni industriji z vidika recikliranja industrijskih in popotrošnih odpadkov za proizvodnjo frotirja. V raziskavi je poudarjen trajnostni pristop k recikliranju industrijskih odpadkov, kot so odpadki pri rahljanju in mikanju vlaken, ter zavrženih oblačil. Reciklirana vlakna so bila predelana v prejo in frotir, ki je bil primerjan s frotirjem iz nerecikliranega bombaža. Frotir iz recikliranega bombaža je bil za malenkost slabšega videza in otipa kot frotir iz nerecikliranega bombaža, druge lastnosti pa so se pokazale kot zelo ponovljive. Analiza stroškov je potrdila izvedljivost proizvodnje srednje- do visokokakovostnega frotirja iz reciklirane preje, ki lahko zagotavlja stroškovno učinkovito zamenjavo nerecikliranega bombaža. Raziskava pripomore k napredku trajnostne proizvodnje tekstilij in poudarja potencial recikliranja za ublažitev vpliva tekstilne industrije na okolje.

Ključne besede: recikliranje, trajnost, bombažni odpadki, frotirna tkanina, stroškovna učinkovitost

1 Introduction

Sustainability has become one of the most critical discussions of today, and is driven by the need to extend the lifecycle of products and reduce waste before those products are discarded. Sustainability encompasses three key aspects: environmental, economic and societal [1]. Embracing these principles requires a commitment to the 3R (reduce, reuse and recycle) or the expanded 4R (reduce, reuse, recycle and rebuy) concepts, with the latter broadening the scope of sustainable practices by encouraging consumers to repurchase recycled goods. The economic, social and environmental benefits of recycling are significant [2]. Recycling contributes to waste reduction and plays a crucial role in the preservation of natural resources [3]. Economically, recycling is often more cost-effective than producing new products from raw materials in some cases, as it conserves energy, reduces production costs and minimizes the financial burden associated with waste disposal facilities. Socially, recycling initiatives create job opportunities and support small business ventures focused on producing recycled goods, thereby enhancing community welfare [4–6].

The global production of textile fibres has risen dramatically, from 23.9 million metric tons (Mt) in 1975 to 98.5 Mt in 2017, driven by increasing fashion demand. This growth has led to significant waste generation, with approximately 26 Mt of garments dumped annually and only 3.5 Mt recycled in 2017. In China, textile waste ranges from 20 to 26 Mt per year, with the recycling rate remaining critically low, while around 45% of produced textiles are wasted. In 2010, textile waste accounted for 13.2 Mt or 5.3% of global municipal solid waste (MSW). Addressing this issue through recycling practices, such as converting textile waste into usable yarns, supports sustainability by reducing landfill use, conserving energy and reducing environmental impacts, in line with circular economy principles [7].

Textile waste presents a significant environmental challenge due to its substantial volume and slow decomposition rate [8]. The fashion industry's rapid cycles and consumer trends contribute to the overconsumption of clothing, leading to increased textile waste generation [9]. The global recycling rates for textile waste remain low, with only 10% of generated clothing waste being recycled, 8% reused and the majority either landfilled or incinerated [10]. Textile waste can be categorized into pre-consumer and post-consumer waste [11]. Pre-consumer waste refers to the waste generated during the production process, from fibre generation to garment manufacturing, and is often recycled into low-grade yarns or used as filling materials for automotive, building insulation and furnishings [12]. Approximately 75% of pre-consumer waste is recycled in this manner. Post-consumer waste, which consists of discarded clothing and textile products, presents a greater challenge, with only 15% being recycled [13]. While thermoplastic polymer-based fibres are commonly recycled due to their ease of processing and ability to be reshaped, natural fibres pose a greater challenge, as recycling processes can compromise their quality [14].

Cotton, a natural fibre known for its softness, absorbency, comfort, breathability and hypoallergenic properties, is highly regarded by consumers, particularly in cotton and cotton-blend apparel [15]. Currently, cotton constitutes 25% of all fibres utilized in textiles, with its consumption steadily increasing in response to global population growth and the gradual recovery from the impacts of COVID-19 in major cotton-consuming nations such as China, Bangladesh, Pakistan, India and Mexico [16]. Additionally, global cotton prices have been on an upward trajectory since July 2021, driven by rising demand [17]. Given the increasing demand for cotton and stringent environmental regulations on waste management, there is a clear need to develop a sustainable strategy for recovering cotton from textile waste through an eco-responsible approach.

Recycling can be achieved by mechanically extracting fibres from waste yarns and fabrics through shredding, a process that forcefully tears the materials back into their original fibre components. However, this method often results in fibres of very short lengths and small fibre clumps, which are unsuitable for spinning into yarns on their own [18]. To overcome this limitation, recycled fibres are blended with virgin fibres, which serve as carriers during the spinning process. However, this approach enables the production of coarser and disoriented yarns [10]. To overcome this issue, ring spinning is the most commonly used spinning system due to its versatility in producing a wide range of yarn types, from low-twist soft and absorbent yarns to highly twisted, coarse or fine yarns [19]. Ring-spun yarns, which lack wrapper fibres, provide a smoother texture for the wearer [20].

Previous research on textile waste recycling has primarily focused on single-source waste streams. This study is innovative, as it comprehensively compares fabrics made from both pre- and post-consumer textile waste, alongside virgin cotton, particularly for terry fabric. This dual-waste approach offers a more holistic perspective on textile waste reuse. A detailed comparison of recycled and virgin yarns was conducted to assess their fibre properties, yarn characteristics and fabric performance, with the aim of demonstrating the potential of recycled fibres for terry fabric production. This study highlights the environmental benefits and economic viability of producing terry fabric from recycled yarn, without compromising fabric quality. The study's findings are readily applicable to existing textile manufacturing processes, making them practical and valuable for industry adoption. By addressing both sustainability and economic aspects, this research provides valuable contributions to the field of sustainable textile production. This paper explores the importance of textile waste recycling and its potential benefits. It delves into the economic and environmental advantages of recycling, while also discussing the challenges and opportunities associated with the recycling method. By understanding the significance of textile waste recycling, we can work towards a more sustainable and circular economy.

2 Materials and methods

The chemicals used in the bleaching process were hydrogen peroxide (50%, Merk, Germany), sodium hydroxide (99%, Sigma Aldrich, USA) and acetic acid (99%, Fisher scientific, UK).The experimentation was carried out by collecting two different types of waste. The waste includes pre-consumer and post-consumer waste. The waste was first converted into fibre, and then spun into yarn. The recycled yarn was then used for the weaving of the final product i.e., terry towels. Pakistani virgin cotton was used as raw material for virgin yarn. The recycling process utilized both pre-and post-consumer waste and involves the steps shown in Figure 1.

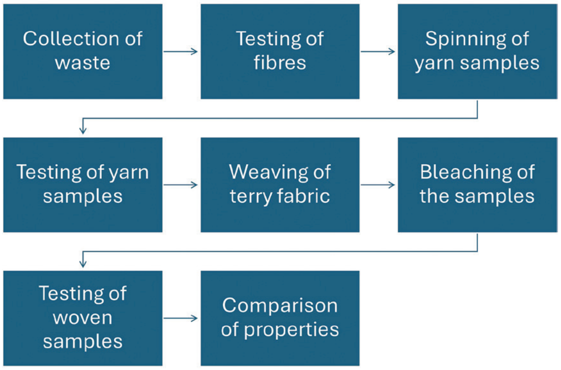


Figure 1: Flowchart illustrating the production of ring-spun yarns from blends of virgin cotton and recycled cotton fibres sourced from pre- and post-consumer textile waste

2.1 Collection of waste

For the preparation of pre-consumer waste (PCW), blow room dropping, card licker and card fly were employed. Approximately 10–11% of the waste from both the blowroom and carding processes was extracted. Post-consumer textile cotton waste was collected from used cotton garments and household textiles and then sorted to remove non-cotton items and heavily contaminated or damaged fabrics. Only 100% cotton textiles were selected, cleaned and processed to remove non-fibrous components before being shredded into fibres for yarn production.

The collection and processing of both pre-consumer and post-consumer textile waste were conducted systematically to ensure efficient reuse. Pre-consumer waste was gathered during the spinning and weaving stages. In the spinning process, blow room, carding and draw frame wastes were collected using suction systems, thereby facilitating their direct utilization. Similarly, warping, sizing and loom selvedge wastes from the weaving process were recovered. Post-consumer waste primarily consisted of garment cutting remnants collected from garment manufacturing facilities. These remnants underwent a manual sorting process to eliminate non-textile and non-cotton components, such as zippers, buttons and synthetic materials.

After sorting, the textile waste was reduced to smaller pieces using a MARGASA MC 1500 machine. The cut pieces were then conditioned by applying 2% water (based on the fabric's weight) and left for at least 12 hours to minimize the risk of fire during shredding. The shredding machine was equipped with carding cylinders fitted with sets of strong, sharp wires arranged in opposing directions. These wires effectively tore the yarns and cut fabric pieces, gradually transforming them into individual fibres through robust carding actions. The sharp wires on the cylinders facilitated this process by applying heavy and abrasive forces. The extracted fibres were subsequently compacted into bales and transported to the mixing room for further processing.

2.2 Process for producing yarn from pre-consumer textile waste

Due to the inadequate quality of pre-consumer fibre, it could not be used alone. Therefore, virgin cotton fibre was added to ensure the overall quality of the yarn. The ratio used for producing pre-consumer yarn consisted of 20% pre-consumer/post-consumer waste fibre and 80% virgin cotton fibre. This consistent mixing ratio was maintained to facilitate a clear and fair comparison between the two types of recycled fibres. During the spinning process, the following specifications were standardized to ensure comparability: the yarn count for all fibres (pre-consumer, post-consumer and virgin) was maintained at the same level, all yarns were ring-spun carded yarns and the mixing percentages for both pre-and post-consumer fibres were identical. The yarn was produced using a ring spinning machine, which is known for its consistent quality and efficiency. The yarn count was set to 49.2 tex (12 Ne), and the twist number was set to 20 TPI, thereby ensuring the required strength and evenness of the yarn. Spinning conditions were maintained under standard industry parameters, with the temperature controlled at approximately 20–22 °C and relative humidity maintained at 65–70%. These conditions were optimized to ensure stable processing and achieve the desired yarn properties for subsequent applications.

2.3 Spinning of yarn

The spinning of pre-consumer, post-consumer and virgin yarns was performed according to the ring spinning method. Yield percentages for pre-consumer, post-consumer and virgin cotton yarns were 81%, 83.5% and 83%, respectively. The blowroom process revealed significant differences between the three yarn types. Pre-consumer yarn experienced increased wastage, decreased growth and decreased staple length. In contrast, post-consumer yarn showed decreased wastage, increased growth and increased staple length. Virgin yarn maintained standard waste, exhibited improved growth and had good staple length. During the carding, drawing/simplex, ring frame and auto cone processes, pre-consumer yarn generally exhibited lower quality, higher wastage and poorer appearance compared to post-consumer and virgin yarns. Post-consumer yarn often had better quality and similar production parameters to virgin yarn, with some exceptions. Overall, virgin yarn consistently demonstrated higher quality, better appearance and similar production performance to post-consumer yarn.

2.4 Terry fabric weaving

To compare the performance of pre-consumer, post-consumer and virgin yarns in terry fabric production, three terry samples were woven using each type of yarn using a rapier weaving machine, which is commonly employed for its flexibility and high precision in fabric construction, especially for complex weave patterns such as terry fabrics. In this setup, Rapier weft insertion was used, a technique that ensures the smooth and efficient insertion of the weft yarn, which is crucial for creating the loops characteristic of terry cloth. The machine was configured with a Twin Beam system, one beam for the ground yarn and the other for the pile yarn, thus facilitating the optimal control of tension and proper loop formation. The 4-Pick Terry Pile Design was employed, which is typical for terry fabrics, as it facilitates the creation of the pile loops needed for high absorbency. The specific terry weave pattern is shown in Figure 2, which illustrates the loop structure and weave configuration used in the fabric. This configuration was chosen to balance fabric strength and softness, providing the necessary properties for towel production. The pre-consumer, post-consumer and virgin samples were constructed under identical parameters to ensure a consistent basis for comparison. All samples were designed with a length of 140 cm, width of 77 cm and a mass per unit area of 500 g/m^2. The hem dimensions (4.5 cm) and type (04-pick terry pile weave design) were standardized, along with the picks per cm (15), pile height (3.8 mm), pile ratio (4 cm per 5 loops) and the total pile yarn length per centimetre (12.2 cm). By maintaining these uniform dimensions and construction attributes, the study ensured that variations in fabric properties were solely attributed to the yarn type, enabling a direct and meaningful comparison of pre-consumer, post-consumer and virgin samples.

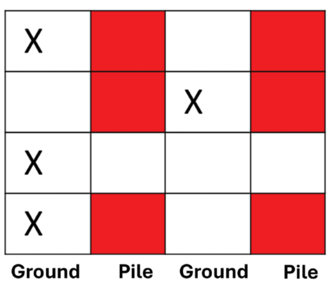


Figure 2: Weave pattern of fabricated terry samples

2.5 Terry finishing process

During processing, only bleaching was performed on the samples. The process involved the use of hydrogen peroxide (50%) as the bleaching agent, along with caustic soda to maintain an alkaline pH and formic acid for pH neutralization after bleaching. The bleaching conditions were standardized for all three samples of 100% cotton to ensure uniformity. The bleaching bath recipe comprised 50 g/L hydrogen peroxide (50%), 2 g/L caustic soda and 1 g/L wetting agent to enhance chemical penetration. The fabric was treated at a temperature of 95 °C for 60 minutes, maintaining a bath pH of around 10.5–11. After bleaching, the fabric was thoroughly rinsed to restore pH to neutral. The bleaching chemicals had a direct effect on the ground of the terry, which was consistent across all three samples of 100% cotton. For this reason, the ratio of chemicals was kept the same for each sample. This process did not significantly affect the pile of the towel. An analysis was performed to evaluate the impact of bleaching on the pile length of terry fabrics, by comparing measurements taken before and after the bleaching process. The study included three sample types: pre-consumer, post-consumer and virgin cotton terry fabrics. Statistical evaluation was conducted using a paired t-test implemented in Python software to assess the significance of the observed changes. The analysis resulted in a p-value of 0.0742, indicating that the changes in pile length were statistically non-significant ($p > 0.05$). These findings suggest that the bleaching process did not have a substantial effect on the pile structure of the terry fabrics.

2.6 Determining the properties of fibres, yarns and fabrics

The collected fibres were characterized using the Advanced Fibre Information System (AFIS) and High-Volume Instrument (HVI) reports. AFIS (e.g., USTER AFIS PRO 2) provided detailed insights into fibre length, fineness, nep content and short fibre content under standard conditions (20 °C ± 2 °C and 65% ± 2% relative humidity), while the HVI (e.g., USTER HVI 1000) evaluated micronaire, strength, elongation, maturity index and trash content under controlled conditions. The prepared yarns were characterized using the USTER Tester 6, which measured yarn evenness, imperfections and hairiness according to the ISO 2060:1994 standard, with samples conditioned under standard laboratory conditions. Additionally, yarn tensile strength was assessed using a single yarn strength tester (e.g., USTER Tensojet) following ASTM D2256, which provide data regarding breaking force and elongation at break. The terry fabric samples underwent dimensional stability testing to washing, conducted according to AATCC Test Method 135-2018, where samples were subjected to repeated washing cycles at 40 °C, with dimensional changes measured after five cycles. Finally, the water absorbency of the terry fabrics was evaluated using the AATCC 79-2018 test method, where a drop test quantified the time taken for complete absorption, indicating the fabric's performance as a terry towel.

3 Results and discussions

3.1 Characterization of fibres

Fibre testing and evaluation were conducted on all three fibres using standard methods, with the results discussed below. Initially, the individual properties of each fibre are presented, followed by a comparative analysis to determine which fibre exhibited the best overall properties. The comparison of the properties of all three fibres revealed that virgin fibre exhibited the best overall characteristics, followed by post-consumer fibre, which had lower properties, and pre-consumer fibre, which had the lowest properties among the three.

Table 1: Comparison of AFIS report parameters of all fibres

Fibre sample	NFE [a] (neps/g)	ASN [b] (µm)	SCN [c] (neps/g)	MLF [d] (cm)	LCV [e] (%)	SFC [f] (%)	Linear density (dtex)
Pre-con	743	733	91	1.65	59.1	39.0	1.65
Virgin	268	741	38	2.33	30.9	7.1	1.67
Post-con	399	645	15	1.98	45.6	23.6	1.67

[a] number of fibre entanglements; [b] average size of neps; [c] seed coat neps; [d] means length of fibre; [e] coefficient of variation of fibre length; [f] short fibre contents

These findings are supported by the Advanced Fibre Information System (AFIS) report (Table 1), which provided detailed insights into various fibre properties such as fibre length distribution, fineness, nep content, trash content, maturity ratio, short fibre content and fibre strength. The AFIS data confirmed that virgin fibre outperformed the other two fibres, particularly in terms of the number of neps per gram (268 number of neps/g) , the average size of neps in microns (741 μm), mean length (2.33 cm), coefficient of variation of fibre length LCV (30.9), short fibre content SFC (7.1%) and finesse (1.67×10^{-6} g/cm), while post-consumer fibre showed a moderate quality and pre-consumer fibre displayed the least favourable results across these parameters. This difference in properties arises because pre-consumer fibres, derived from spinning waste, generally exhibit inferior characteristics compared to both virgin and post-consumer fibres. Their source material often includes shorter and weaker fibres, resulting in reduced strength, poor length uniformity and lower durability. In contrast, post-consumer fibres, obtained from highly finished textile garments, benefit from higher-quality input materials. Although they are slightly lower in quality than virgin fibres, post-consumer fibres demonstrate improved performance in terms of fibre strength, length and overall integrity due to the superior quality of their source materials and the processing methods involved.

The comparison of the High Volume Instrument (HVI) reports (Table 2) for all the fibres indicates that pre-consumer fibre exhibited the lowest quality properties compared to post-consumer and virgin fibres, with virgin fibre demonstrating the best overall qualities. The HVI report provides a comprehensive analysis of key parameters such as fibre length, uniformity index, strength, micronaire, colour grade, trash content, reflectance (R_d) and yellowness (+b). These metrics reveal that virgin fibre outperforms the others in terms of length consistency, tensile strength, fineness and colour quality, while pre-consumer fibre falls short in these areas, highlighting its lower overall quality.

In the spinning process, the highest quality raw material is utilized for production, while the leftover material, known as spinning waste, is recycled into pre-consumer fibre. Since pre-consumer fibre is derived from this leftover waste, which often contains dust and other impurities, it exhibits lower properties compared to post-consumer and virgin fibres [21]. Post-consumer fibres, on the other hand, possess superior qualities because they are recycled from used garments, which were originally high-quality products [22]. Additionally, used garments generally contain fewer impurities, contributing to the better properties of post-consumer fibres in comparison to pre-consumer fibres [23]. Given the inherent differences in the properties of pre-and post-consumer fibres, both are blended with a specific percentage of virgin fibre to enhance their spinnability. To ensure consistent the comparability of results, the same mixing ratio was maintained for both pre-and post-consumer fibres.

Table 2: Comparison of HVI report parameters of all fibres

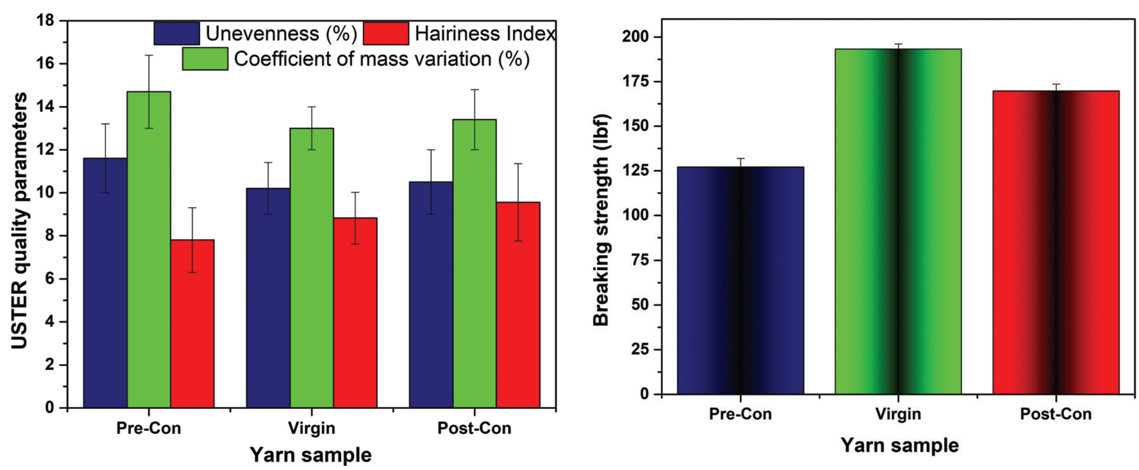
Fibre sample	MIC a)	MI b)	SCI c)	L d) (cm)	UI e)	SFI f)	σ g) (g/tex)	ϵ h) (%)	M i) (%)	R_d j)	+b k)
Pre-con	4.27	0.85	6	2.23	65.6	35.8	23.4	5.6	5.7	53.9	9.7
Virgin	4.27	0.87	105	2.57	80.3	10.6	27.6	4.6	6.1	69.3	9.9
Post-con	4.14	0.86	63	2.38	71.7	19.0	28.0	4.3	6.1	71.2	9.3

a) micronaire, b) maturity index, c) spinning consistency index, d) staple length, e) uniformity index, f) short fibre index, g) strength, h) elongation, i) moisture, j) reflectance, k) yellowness

3.2 Characterization of yarns

The comparison of the USTER reports properties shown in Figure 3a for the three yarns indicates that virgin yarn exhibited the best overall properties, with superior evenness, lower imperfections and better strength. For instance, the unevenness percentage (U%) for virgin yarn is 10.2, yarn coefficient of mass variation (CVm%) is 13 and the Hairiness Index (H Index) is 8.82, reflecting its high quality. Post-consumer yarn, while slightly lower in quality than virgin yarn, still maintains better properties than pre-consumer yarn, with a U% of 10.5, CVm% of 13.4 and an H Index of 9.55. In contrast, pre-consumer yarn demonstrates the lowest quality, with a U% of 11.6, CVm% of 14.7 and an H Index of 7.8. This difference in properties arises because pre-consumer fibre, derived from spinning waste, generally exhibits inferior characteristics compared to both virgin and post-consumer yarn. Its source material often consists of shorter and weaker fibres, which negatively affect the yarn's strength, evenness and durability. On the other hand, post-consumer yarn, obtained from highly finished textile garments, benefits from higher-quality input materials. Although it is slightly lower in quality than virgin yarn, post-consumer yarn demonstrates improved performance in terms of yarn evenness, tensile strength and overall durability due to the superior material quality of its source.

The comparative analysis for breaking strength shown in Figure 3b reveals that virgin yarn exhibited the highest strength among the three types, with a breaking strength of 158 N, breaking tenacity of 0.443 N/tex and a breaking factor of 10400 Ntex. This superior strength can be attributed to the high-quality raw materials used, which contributed to its enhanced performance [24]. Post-consumer yarn, while showing lower strength compared to virgin yarn, demonstrated better properties than pre-consumer yarn, with a breaking strength of 754.4 N, breaking tenacity of 0.387 N/tex and a breaking factor of 9190 Ntex. This is due to the fact that post-consumer yarn is derived from previously high-quality garments, which retain more desirable characteristics despite being recycled. In contrast, pre-consumer yarn exhibited the lowest strength, with a breaking strength of 565 N, breaking tenacity of 0.291 N/tex and a breaking factor of 6832.4 Ntex. The reduced strength of pre-consumer yarn can be attributed to the lower quality of the waste material used, which often includes various impurities and shorter fibre lengths, which affect the overall yarn strength [25].



a) b)

Figure 3: Yarn test results: a) USTER quality parameters; and b) breaking strength

3.3 Dimensional stability of terry fabric

The dimensional stability of three terry fabrics (pre-consumer, post-consumer and virgin samples) was analysed according to Table 3. All three fabrics exhibited similar shrinkage percentages in both length (approximately 5.38%) and width (between -1.67% and -1.80%). Based on the data, no significant difference in dimensional stability between the three fabric types was recorded.

Table 3. Comparison of dimensional stability of the prepared terry samples

Dimensional stability of the terry fabric	Pre-consumer sample			Post-consumer sample			Virgin sample		
	Before wash	After wash	Shrinkage (%)	Before wash	After wash	Shrinkage (%)	Before wash	After wash	Shrinkage (%)
Length (± 6%)	139.6	132.1	-5.38	139.4	131.9	-5.38	139.4	131.9	-5.38
Width (± 4%)	72.2	70.9	-1.80	72.0	70.8	-1.67	72.0	70.8	-1.67

3.4 Absorbency test

The water absorbency of terry fabric from virgin, pre-consumer and post-consumer waste yarns was evaluated using the weight gain method. Fabric samples of standard dimensions (10 cm × 10 cm) were first dried in an oven at 105 °C for two hours to remove any residual moisture. The dry weight of each sample (W_{dry}) was recorded using a precise balance. The samples were then fully submerged in distilled water at room temperature (25 °C) for one minute to ensure saturation. After immersion, excess surface water was gently removed by pressing the sample between blotting papers, without squeezing the internal water, and wet weight (W_{wet}) was recorded. The water absorbency (%) was calculated using equation 1:

$$Water\ absorbency = \frac{(W_{wet} - W_{dry})}{(W_{wet})} \times 100\ (\%) \qquad (1)$$

A comparative analysis of absorbency was conducted on three terry fabrics (pre-consumer, post-consumer and virgin) and is presented in Figure 4. The results indicated that the virgin fabric exhibited the highest absorbency (70%), followed by the post-consumer fabric (68%). The pre-consumer fabric displayed the lowest absorbency (62%). Notably, the post-consumer fabric demonstrated comparable absorbency to the virgin fabric. These findings suggest that recycled yarn derived from post-consumer waste can serve as a viable alternative to virgin yarn for the pile component of terry fabric. The absorbency of fabrics is influenced by multiple factors, including yarn structure, fibre properties, fabric density and the surface treatment of the material. The results observed in this study can be attributed primarily to differences in yarn structure and the properties of fibres derived from virgin, post-consumer and pre-consumer sources. The yarn structure plays a significant role in absorbency. Virgin yarn, characterized by its lower unevenness percentage (U%), coefficient of mass variation (CVm%) and moderate hairiness index (H Index), results in a more uniform and compact structure. This uniformity enables the fabric to retain moisture effectively without gaps that hinder water wicking. In contrast, post-consumer yarn, though slightly less uniform than virgin yarn, still exhibits sufficient structural integrity to support good absorbency. Pre-consumer yarn, with its higher unevenness and CVm% values, creates more irregular spaces within the fabric, leading to reduced capillary action and hence lower absorbency.

In addition to yarn properties, fabric density and porosity also significantly influence absorbency. Higher-density fabrics tend to trap more water, while excessive porosity in fabrics made from pre-consumer yarn may cause faster drainage, thereby limiting water retention. The virgin fabric's superior absorbency can also be attributed to its smoother surface finish, which minimizes resistance to water penetration, compared to the rougher surfaces found in fabrics made from recycled yarns.

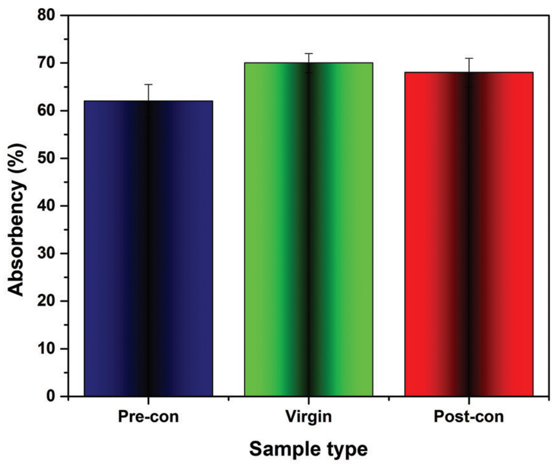


Figure 4: Comparison of absorbency results for the prepared terry samples

3.5 Tensile strength

Tensile strength was measured using a Universal Testing Machine (UTM), following the ASTM D5035 standard, where fabric samples were subjected to a constant rate of extension and the maximum force before breakage was recorded. The terry fabrics made from the virgin yarn exhibited the highest tensile strength of 0.954 MPa due to the superior quality and uniformity of the fibres. Post-consumer yarn showed slightly lower tensile strength of 0.890 MPa, as it is derived from recycled garments, but still retains a relatively high-quality fibre. Pre-consumer yarn, made from spinning waste, demonstrated the lowest tensile strength of 0.784 MP due to the presence of shorter, weaker fibres and higher yarn irregularities. These differences reflect the impact of fibre quality and yarn structure on fabric strength.

3.6 Cost analysis of yarn samples

The cost analysis of the three yarn types (shown in Table 4) reveals that the highest profit margin is obtained through the recycling of pre-consumer waste. Despite pre-consumer yarn exhibiting lower properties than post-consumer and virgin yarns, it proves well-suited for upcycling, thereby addressing both economic viability and sustainability objectives. Products typically manufactured from virgin and post-consumer yarns can be effectively substituted with those made from pre-consumer yarn, which offers comparable properties while optimizing profit margins. This strategy not only enhances profitability but also aligns with environmental and user-friendly principles. It can thus be concluded that recycling both pre-and post-consumer waste enables the production of environmentally sustainable and cost-effective yarns, and thus results in higher profitability than virgin yarns while advancing sustainability and recycling goals.

The following equations were used in calculating the cost analysis:

i. Net cost per kilogram (EUR):

Net cost/kg = Price/kg + Transport expenses/kg + Spinning cost/kg + Cotton cost/kg + Conversion cost/kg + Packing cost/kg (2)

ii. Net profit per kilogram (EUR):

Net profit/kg = Price/kg - Net cost/kg (3)

iii. Profit per frame (EUR):

Profit/Frame = Net profit/kg × Production per frame (kg) (4)

iv. Profit per bag (EUR):

Profit/Bag = Net profit/kg × Bag weight (kg) (5)

3.7 Cost analysis of terry fabric

The cost analysis of terry fabric conversion (Table 5) reveals that utilizing pre-consumer yarn as the pile yarn results in the highest profit margin compared to the use of virgin or post-consumer yarn. This finding is corroborated by the test results for the terry samples, which demonstrate that the properties of fabric produced from pre-consumer yarn are nearly equivalent to those of fabrics made from virgin and post-consumer yarns. Consequently, pre-consumer

Table 4: Cost analysis of prepared yarn samples (pre-consumer, post-consumer and virgin)

Costing value	Virgin yarn	Pre-cons yarn	Post-cons yarn
Price (EUR/kg)	1.156	1.03	1.10
Transport expenses (EUR/kg)	0.014	0.01	0.01
Sp cost (EUR)	0.084	0.08	0.08
Cotton cost (EUR/kg)	1.254	1.12	1.20
Conversion cost (EUR/kg)	0.155	0.16	0.16
Packing cost (EUR/kg)	0.014	0.01	0.01
Net cost (EUR/kg)	1.422	1.30	1.37
Sale price (EUR/kg)	1.735	1.67	1.70
Net profit (EUR/kg)	0.312	0.37	0.34
Production (kg/frame)	836.68	798.05	817.37
Profit (EUR/frame)	261.18	295.32	273.98
Profit (EUR/bag) (1 bag = 45.37 kg)	14.16	16.79	15.21

Table 5: Costing of prepared terry fabric samples (conversion of yarn to fabric)

Costing value	Virgin yarn	Pre-con	Post-con
Yarn price/kg for ground (EUR)	0.498	0.498	0.498
Yarn price/kg for pile (EUR)	1.735	1.664	1.702
Yarn price for terry fabric (50%ground + %50% pile) (EUR)	1.116	1.081	1.099
Terry fabric conversion cost@Euro 0.297/kg (EUR)	0.297	0.297	0.310
Wastage % of terry (EUR)	0.013	0.014	0.014
Bleaching and dyeing cost@Euro 0.254/kg avg (EUR)	0.255	0.255	0.255
Wastage % of wet processing	7	7.75	7.1
Total wastage (%)	11.10	12.25	11.40
Total Conversion cost of processed terry/kg (EUR)	0.552	0.552	0.565
Finished terry fabric cost (EUR)	1.792	1.752	1.785
Sales price of terry fabric/kg (EUR)	2.249	2.249	2.249
Cost/kg of terry fabric	0.457	0.496	0.464
Profit as a ratio relative to the virgin (%)		8.6	1.5

yarn presents a viable substitute for virgin yarn in terry fabric production, thereby providing a cost-effective and sustainable alternative, without compromising fabric quality.

3.8 Comparison with other recycling methods

Various technologies are employed to break down textiles and convert them into reusable products, each offering unique advantages and facing distinct challenges. These aspects are systematically summarized in Table 6, which provides a comparative overview of their strengths, limitations and suitability for specific applications.

Table 6: Pros and cons of different textile recycling technologies

Recycling method	Pros	Cons	Reference
Pyrolysis	A simple process that can be applied to a broad range of materials without requiring prior treatment of textile waste.	Requires a high-temperature chemical reaction that demands excessive electrical power.	[26]
Hydrothermal	This method produces low ash while operating at a lower temperature compared to pyrolysis.	Involves a long reaction time and results in reduced purification.	[27]
Biological	This method offers an eco-friendly solution with a high potential for removing dyes from clothing during textile recycling.	This method generates toxic intermediates at a high cost and with a longer retention time.	[28]
Mechanical	The physical method of textile recycling is eco-friendly, economical and facilitates easy quality control, without requiring chemicals or high temperatures.	Collecting and segregating waste is a challenging task.	This work

4 Conclusion

In conclusion, this study successfully developed a sustainable and cost-effective terry fabric using yarns spun from pre- and post-consumer textile waste. A comprehensive evaluation of fibres, yarns and fabrics was conducted, including HVI and AFIS reports for fibres, USTER tests and tensile strength measurements for yarns. The fibre analysis revealed that pre-consumer fibres exhibited lower quality than post-consumer and virgin fibres. However, blending 80% virgin fibre with recycled fibres resulted in yarns with comparable yields and production rates. Tensile strength measurements of the terry fabrics confirmed that both pre-consumer (0.784 MPa) and post-consumer (0.890 MPa) recycled yarns produced fabrics with mechanical properties comparable to those of virgin cotton (0.954 MPa), supporting their durability and suitability for end-use applications. Further testing, including absorbency and washing durability, showed no significant differences between terry fabrics made from pre-consumer, post-consumer and virgin yarns. The results indicated that the virgin fabric exhibited the highest absorbency (70%), followed by the post-consumer fabric (68%) and the pre-consumer fabric with the lowest absorbency (62%). The dimensional stability analysis of the three terry fabrics revealed consistent shrinkage percentages in length (approximately 5.38%), with no significant differences observed among them. These results indicate that the evaluated properties – mechanical strength, absorbency and washing durability – are sufficient to validate the use of terry fabrics developed from pre- and post-consumer waste as performance-ready materials for end-use applications. Importantly, the production process required no significant adjustments to machine settings or chemical processes, regardless of the yarn type, thereby reinforcing the practicality of integrating recycled fibres into existing manufacturing systems. Moreover, terry fabrics developed from pre- and post-consumer waste not only exhibit comparable performance in terms of other properties but also offer significant economic advantages, with profit margins of 8.6% and 1.5%, respectively, relative to virgin cotton samples. These economic benefits underscore the potential of recycled fabrics as a cost-effective and sustainable alternative in the textile industry. These findings highlight the potential of using recycled fibres in terry towel production as a sustainable and cost-effective alternative to virgin cotton, ensuring quality and durability while contributing to circular economy practices in the textile industry.

Limitations and future prospects

This study faced a few limitations. First, the quality of pre-and post-consumer waste was inconsistent due to variability in source materials, which could affect reproducibility. Second, ¸the mechanical shredding of fibres resulted in reduced fibre length and strength, necessitating blending with virgin fibres for acceptable yarn quality. The bleaching process applied uniform chemical ratios across all samples, which may not fully address the variability in contamination levels or initial fabric compositions. Additionally, the scope of testing was limited to mechanical and absorbency properties, ignoring other aspects such as durability under extended usage.

Future research could explore advanced recycling technologies, such as enzymatic or chemical methods, to enhance the quality of recycled fibres and minimize reliance on virgin fibres. Industrial-scale trials are needed to validate the commercial feasibility of the processes developed in this study. Comprehensive life-cycle analyses, including environmental impact assessments, such as water and energy savings and carbon footprint reduction, could further substantiate the sustainability claims. Expanding the application of recycled yarns to other textile products, such as upholstery or technical fabrics, could demonstrate their versatility.

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