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Comparative analysis of structural, thermal, and electrical characteristics of virgin and recycled polyester yarns

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This study presents a comprehensive comparison between virgin and recycled polyester yarns in both filament and staple forms, focusing on their mechanical, electrical, thermal, and structural properties. Yarn samples produced from mechanically recycled PET bottles and virgin polyester were evaluated in terms of tensile strength, elongation, and surface resistivity. In addition, thermal behavior was analyzed using thermogravimetric analysis (TGA), and crystallinity was examined through X-ray diffraction (XRD). The results showed that recycled polyester yarns exhibited lower tensile strength but higher elongation than virgin counterparts. Recycled samples also demonstrated lower surface resistivity, indicating better electrostatic dissipation characteristics. TGA revealed a lower decomposition temperature and higher residual mass in recycled samples, while XRD analysis confirmed reduced crystallinity compared to virgin polyester. These findings provide valuable insight into the performance characteristics of recycled polyester yarns and their suitability for various applications within sustainable textile production.

Keywords: Recycled polyester, Surface resistivity, TGA, Virgin polyester, XRD, Yarn properties

1 Introduction

Global warming is a major subject on all societal levels, including governments, economic actors, and citizens. Over the last two decades, driven by the raised awareness of environmental, social, and economic issues, the concept of sustainability has reached a high level of dissemination and interest within organizations. The awareness of global warming is omnipresent in political strategies, and it is increasing more and more in consumer choices. The growing awareness among consumers regarding the social and environmental impacts of fashion consumption has significantly influenced purchasing decisions toward ethical and sustainable fashion. Despite this, consumption of mass-market products is growing, and global Greenhouse Gas (GHG) emissions continue to grow. Textile companies launch new items with a short product life cycle, leading to less durable quality and more costs. So, the consumption of textile items and the waste of textile products have been rising dramatically. Sustainable development concerns such as climate change and increasing carbon emissions have forced companies to change their way of doing business from a linear economy to a circular economy (CE). In this context, the textile industry is the second largest sector of the global trade market in terms of economic activities[1-5].

Furthermore, improved standard of living and global population growth has led to increased textile consumption and production in recent years. Nevertheless, the textile and fashion industry is among the leading polluting sectors, so all the phase of the fashion and textile supply chain endangers our resources and the planet. Textile and apparel industries generate environmental harm at all stages of production, from raw material cultivation to disposal of finished goods. Large amounts of chemical loads, high amounts of water usage, high energy consumption, air emission, solid waste, and odor formation are the major environmental challenge in textile industries[3, 5, 6].

Raising environmental awareness and fashion trends are two main reasons for the increasing demand for recycled products. Many companies are launching their collections made of recycled materials. When considering consumption rates, polyester is the essential fibre for the recycling market. It is claimed that using recycled fibre in

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apparel is one of the most important ways to ensure the sustainability and circular economy in the textile industry based on energy savings, water savings, and reduced CO_2 emissions[7,8]. On the other hand, recent research has revealed the adverse effects of recycled polyester on the environment. According to that research, rPET (Recycled Polyethylene Terephthalate) fabrics release 2.3 times more microfibres than virgin PES during household washing[9]. Recently, Heather et al. studied the discovery and quantification of plastic particle pollution and measured plastic particles ≥700 nm in whole human blood from 22 healthy volunteers. Finally, they identified and quantified four high-production volume polymers applied in plastic for the first time in blood. PET was the most widely encountered (>LOQ values in 50% of all tested donors), followed by polymerized styrene (PS) (36%), polyethylene (PE) (23%), and poly methyl acrylate (PMMA) (5%).The maximum concentration of PET analyzed in a blood sample was 2.4 µg/mL; for PS, this was 4.8 µg/mL; for PE, this was 7.1 µg/mL.The mean sum concentration for each donor was 1.6 µg total plastic particles/mL blood sample. It indicates that at least some of the plastic particles humans come in contact with can be bioavailable and that the rate of elimination via, e.g., the biliary tract, kidney, or transfer to and deposition in organs is slower than the rate of absorption into the blood[10]. Fibres that are shed from textiles and garments, especially microfibres, are ubiquitous in air, soil, rivers, lakes, and oceans and are regarded as anthropogenic litter that has become a global concern for the sustainability of the textile and fashion industry. There is clear evidence that microfibres as emerging contaminants are widely distributed in the marine environment globally. So, textiles are estimated to be the largest microfibre source in the background[11].

PET recycling involves collecting used PET products, processing them into new materials, and then using them to manufacture new products. However, despite its importance, the recycling of PET faces numerous challenges that hinder its effectiveness on a global scale[12]. There are four ways of recycling PET bottles: mechanical, semi-mechanical, back to the oligomer, and back to the monomer. The last two, grouped under chemical recycling, can produce finer fibres having properties almost similar to those of virgin PET fibres. However, chemical recycling of PET causes more environmental burdens than mechanical recycling. In the case of the mechanical recycling method (MRM), the waste bottles are recycled directly as polymer feed through grinding, cleaning, separating, dehydrating, drying, and remelting. In such recycling methods, cleaning contaminants and controlling moisture content (0.8%) is important for good quality recycled chips. In contrast, in the case of chemical recycling, depolymerization of PET polymer takes place with different techniques, and the polymer is broken down into monomers and oligomers. The important advantage of chemical recycling is the possibility of getting virgin PET quality, even though the MRM is a cheap and simple process[13]. However, there is limited academic literature available on comparing the performance characteristics of rPET and vPET yarns[14,15]. Therefore, this study presents a comparative analysis of virgin and recycled polyester yarns, covering both filament and staple types. Unlike previous research that addresses limited property sets or single yarn forms, this work combines mechanical, thermal, electrical, and structural evaluations. The approach includes tensile testing, thermogravimetric analysis, X-ray diffraction, and surface resistivity measurements. The results offer a comprehensive understanding of material performance.

2 Materials and Methods

The experimental process started with the selection of virgin and recycled polyester yarns, categorized into filament and staple forms. These yarns were produced from vPET and rPET fibres, obtained through the mechanical recycling of PET bottle waste. All samples were knitted under the consistent conditions to ensure comparability. Tensile strength and elongation at break were evaluated according to the ISO 2062 standard. Electrical properties were assessed via surface resistivity measurements in accordance with the TS EN 1149-1. Thermal behavior was analyzed using a HITACHI STA 7300 instrument, and structural characteristics were examined by X-ray diffraction using a Rigaku Miniflex 6000 diffractometer.

The staple yarn samples were produced by using a ring-spinning frame. The yarn types and properties are presented in Table 1.

2.1 Breaking Strength and Elongation Test

Tensile strength and elongation at break were measured using a Titan Universal Strength Tester. in accordance with ISO 2062. All tests were performed under standard atmospheric conditions for textiles

Table 1 — The yarn types and properties

Type of Yarns	Fibre Linear Density, dtex	Number of Filament	Virgin PES Yarn, vPET
Multi-filament	4.17	36	150 dtex
		72	300 dtex
Staple	1.2		Ne 28
			Ne 40

Table 2 — Surface resistivity classification of materials[15]

Classification	Surface Resistivity, Ω
Conductive	$<10^5$
Dissipative	10^5 to 10^{12}
Insulating	$>10^{12}$

(20 ± 2°C temperature and 65 ± 4% relative humidity), as defined by ISO 139. Each sample was conditioned in this environment for at least 24 h prior to testing. All yarn samples were tested 20 times, and results were analyzed statistically.

2.2 Surface Resistivity Tests

The yarn samples were knitted in a single jersey for surface resistivity measurement. The conductivity of the samples was measured using an ELME MULTIMEG megohmmeter at 55.0% relative humidity (RH) and 20.0°C. The surface resistivity test carried out according to the "TS EN 1149-1: Electrostatic properties- Part 1: surface resistivity" standard. Due to constraints, this test has been conducted only on fabrics produced from staple fibres. The measurements were repeated 10 times for each sample. The samples were classified according to their resistivity (Ω), as shown in Table 2.

2.3 X-Ray Diffraction Analysis (XRD)

XRD is an analytical technique used to analyze and determine the crystal structures of materials. The main purpose of XRD is to determine the crystal structures, internal arrangements, and atomic ordering of a material's crystal lattice. This technique is widely employed as a research and characterization tool for investigating the structural properties of solid materials with crystal structures. Therefore, XRD analysis was applied to four rPET and vPET fabric samples. Measurements were carried out on a single sample per yarn type. All scans were performed using identical settings to maintain consistency in data collection. The samples were compacted under nominal hand pressure and then transferred to the sample holder. X-ray diffractograms were obtained using a Rigaku Miniflex 600 X-ray diffractometer. X-ray diffraction was performed using a Rigaku MiniFlex 600 diffractometer with Cu-Kα radiation at 40 kV and 15 mA. Samples were gently pressed and mounted on a flat sample holder to ensure a uniform surface. The scan was carried out in the range of 10°–90° (2θ), with a step size of 0.02° and a scan speed of 2.5°/min. The crystallinity index (CI) of the samples was calculated using X-ray diffraction (XRD) data in the 2θ range of 10°–30°. Crystalline and amorphous regions were separated using peak deconvolution. The CI was determined using the Hermans and Weidinger equation:

$$CI\ (\%) = \frac{A_c}{A_c + A_a} x\ 100\%. \qquad ..(1)$$

where A_c and A_a represent the integrated areas of the crystalline and amorphous peaks, respectively. This method is widely accepted for PET-based polymers due to its simplicity and reproducibility[16,17].

2.4 Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) measures the amount and rate of weight change in a material as a function of temperature or time in a controlled atmosphere. This technique provides valuable information about the thermal stability and composition of materials, as well as their decomposition temperatures and mechanisms. TGA is performed by heating a sample in a controlled environment and measuring its weight change over time. TGA data is typically presented as a graph of weight change versus temperature. HITACHI STA 7300 thermogravimetric analyzers were used in tests. TGA was performed on one representative sample for each yarn type. The test was conducted under the consistent conditions to ensure comparability across samples.

The analysis followed a three-stage temperature program designed to comprehensively examine the thermal behavior of the material. In the first stage, the temperature was increased from 30 to 550°C at a constant heating rate of 10 °C per min. This stage aimed to determine the weight loss patterns and the onset temperatures of thermal decomposition. Once the temperature reached 550°C, the system was maintained at a constant temperature for 10 min. This stabilization phase was implemented to ensure that all thermal reactions were fully completed and to enable a detailed observation of the decomposition process. Following this, the temperature was reduced from 550 to 100°C at a cooling rate of 30°C per minute. This cooling phase was designed to assess the post-decomposition thermal stability of the sample and facilitate its transition to a lower temperature

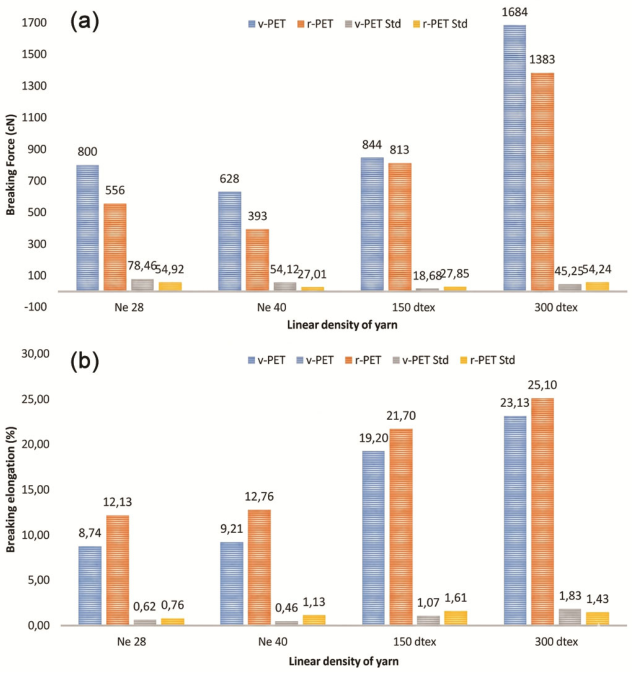

Fig. 1 — Mean breaking force (cN), elongation at break (%), and standard deviation (Std) of vPET and rPET yarn samples. rPET samples exhibit higher elongation but lower strength values compared to vPET

range. In the final stage, the temperature was further decreased from 100 to 30 °C at the same cooling rate (30 °C per min). This complete thermal cycle was designed to evaluate the material's behavior under thermal stress, including its residual weight after decomposition and its structural stability.

3 Results and Discussion

3.1 Yarn Breaking Strength and Elongation

The Kolmogorov-Smirnov test was performed to check the normal distribution of the data, and it was determined that the data follows a normal distribution. A paired-sample t-test was conducted to compare the strength and elongation values of matched rPET and vPET yarn samples with the same linear density. The results revealed statistically significant differences between rPET and vPET yarns' breaking force (cN) and elongation (%) values. Independent of linear density, filament, and staple vPET yarns exhibited significantly higher breaking strength and lower elongation than rPET yarns. The means of breaking force/elongation and strength values are given in Fig. 1 and 2, respectively.

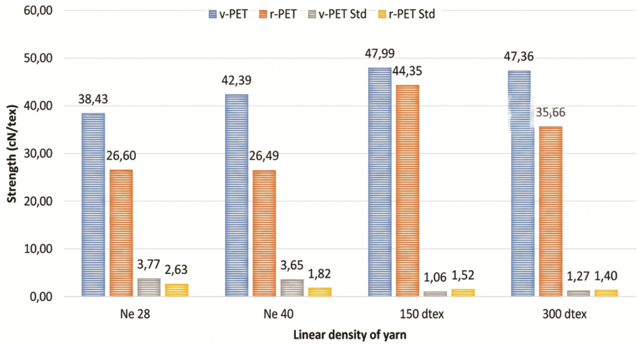

Fig. 2 — Breaking Strength(cN/tex) values and standart deviations (Std) of vPET and rPET yarn samples

The higher elongation percentages exhibited by the rPET yarns compared to the vPET yarns, can be attributed to several factors. One possible reason is the presence of structural irregularities and variations in the recycled polyester fibres due to the recycling process. These irregularities can lead to a more flexible and less uniform fibre structure, resulting in increased yarn elongation. As mentioned previously, during the recycling process, the thermal and mechanical stresses can cause degradation of the polymer chains and breakage of molecular bonds in the polyester fibres. This can result in shorter chain lengths and lower molecular weight, leading to a reduction in the overall stiffness of the recycled polyester fibres. The reduced stiffness allows for greater deformability and elongation of the yarn during tensile testing. The recycling process may also introduce impurities or contaminants into the rPET fibres. These impurities can affect the mechanical properties by influencing the intermolecular interactions and overall fibre structure. Contaminants or additives from previous product life cycles can alter the polymer characteristics and contribute to increased elongation in the resulting yarn.

Based on the conducted analyses, it was observed that an increase in linear density, depending on the fibre count in the cross-section, enhances the breaking strength. This enhancement is more prominent in PES filaments. Previous research noted that thermal exposure and shear degradation during recycling decrease the fibre's average molecular weight, molecular chain length, and crystallinity[18]. These structural changes occur during recycling process significantly impact the mechanical properties of the fibre. So, rPET exhibits lower breaking strength and higher elongation compared to vPET. In a previous study, two equivalent fabrics were developed using rPET and vPET fibres and compared their mechanical properties. The researchers found that the vPET fabric

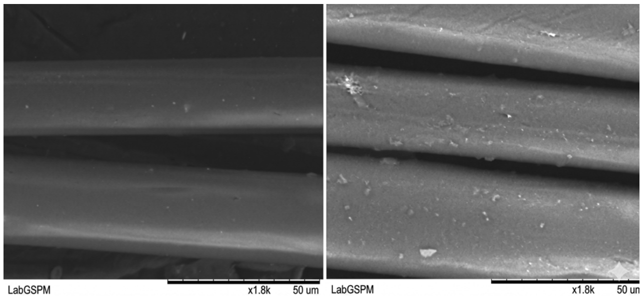

Fig. 3 — Images at1800× magnification of vPET (left) and rPET (right) staple fibres[20]

samples presented slightly higher dynamic force (cN/g.m^{-2}) in warp and weft directions than rPET fabric samples. They also found that the rPET fabric samples presented significantly more (approx. 22%) breaking elongation than vPET fabric samples. In the study, it is explained this might be due to the lower amorphous/crystalline ratio in the rPET fibre that makes it easier to be extended[19]. These findings in the literature support the findings in our study.

Furthermore, the surface structure of rPET fibres appears dull and exhibits more surface deformation than vPET, as illustrated in Fig. 3[20,21]. As a result, doubling the fibre count in the cross-section results in an approximate 1.7 times increase in the maximum force (in cN) the yarn can withstand. For polyester, this ratio exceeds 1.9 times. In contrast to filament structures, staple yarns demonstrate distinct behavior due to the cohesion (radial forces) generated by twisting, which limits inter-fibre slippage and provides the yarn with greater stability against applied forces.

3.2 Surface Resistivity Results

The surface resistivity results indicate that rPET yarns generally exhibit lower surface resistivity compared to vPET yarns. Specifically, the Ne 28/1 rPET yarns showed a mean resistivity of $2.88 \times 10^{9} \Omega$, classifying them as dissipative. The Ne 40/1 rPET yarns had a higher mean resistivity of 2.01×10^{10} Ω, still within the dissipative range. In contrast, the vPET yarns exhibited significantly higher resistivity values, with most measurements exceeding 2.00×10^{12} Ω, classifying them as insulating. The Ne 40/1 vPET yarns showed a mean resistivity of 1.34×10^{11} Ω, which also falls into the insulating category.

Filament yarns showed a similar trend. The 300 dtexrPET filament had an average resistivity of 1.43×10^{10} Ω, while the 150 dtex rPET was higher, averaging 3.71×10^{11} Ω. All virgin PET filament samples exceeded 10^{12} Ω, classifying them as insulating.

rPET yarns exhibit better conductive properties than vPET yarns due to structural differences arising from the recycling treatments. Recycling process reduces fibre crystallinity by disrupting the ordered crystalline regions, increasing the proportion of amorphous regions. Virgin polyester fibres, produced under the controlled conditions, have higher crystallinity and more stable molecular structures. Therefore, rPET fibres also show higher moisture regain due to structural irregularities and impurities introduced during recycling, creating more hygroscopic sites. This increased moisture lowers surface resistivity by facilitating ionic conduction. rPET has more amorphous regions, which accommodate more water; as studies have shown, materials with higher crystallinity retain less moisture[22]. The greater water content provides more mobile ions, enhancing ionic conduction and so lowering surface resistivity[23].

3.3 Thermogravimetric Analysis (TGA)

The TGA patterns for both vPET and rPET samples are given in Fig. 4. The TGA analysis highlights notable numerical differences in their thermal and structural behavior. For vPET, the initial weight loss below 100°C is minimal, approximately 0.1-0.2%, indicating very low moisture absorption. In contrast, rPET exhibits a higher weight loss in the same range, around 0.3-0.5%, reflecting its greater moisture content due to the increased presence of amorphous regions that trap moisture more effectively.

The onset of decomposition further underscores the differences in thermal stability. For vPET, the onset of degradation was observed at approximately 390 °C, with a peak decomposition temperature near 435 °C and a residual weight of around 0.2%. In comparison, the rPET sample exhibited a slightly lower degradation onset at 388 °C, a maximum decomposition rate near 441 °C, and a higher residual weight of 0.8%. These differences suggest minor thermal instability in rPET, likely due to molecular chain scission and processing-related impurities.

This observation aligns with the research of Santos *et al.* (2022)[24] that found rPET materials typically degrade at slightly lower temperatures than virgin PET. This situation is likely due to the presence of non-volatile pollutants or additives that arise during the recycling process.

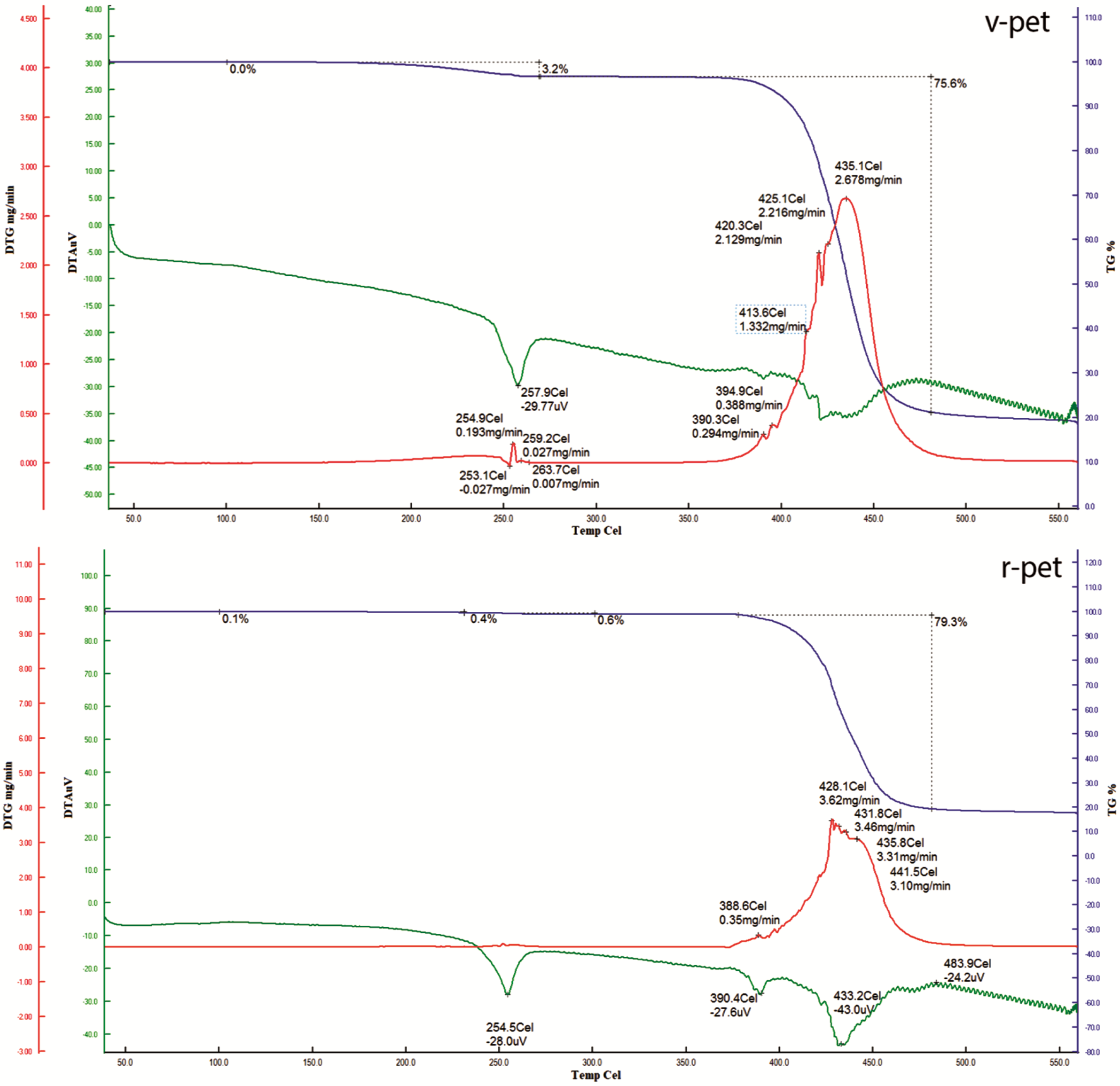

Fig. 4 — Thermogravimetric analysis (TGA) curves of vPET and rPET yarns. Decomposition onset temperature and residue percentages are indicated, showing higher thermal stability in vPET

As a result, rPET absorbs roughly more moisture and retains more residual weight than vPET, while vPET decomposes at a temperature approximately 30°C higher than rPET. These quantitative differences emphasize the structural advantages of vPET, including its higher crystallinity and thermal stability, compared to the more flexible but less stable rPET, which contains a greater proportion of amorphous regions and impurities from the recycling process.

3.4 X-ray Diffraction (XRD) Analysis

The XRD patterns for both rPET and vPET fibres are shown in the Fig. 5. The analysis provides insights into the crystallinity and structural arrangement of the fibres. The XRD patterns of vPET fibres exhibit sharper and more intense peaks compared to rPET fibres. This indicates that vPET fibres have a higher degree of crystallinity due to the controlled manufacturing processes that avoid degradation and contamination. The peaks in the XRD pattern of rPET fibres are broader and less intense. This suggests a higher proportion of amorphous regions in rPET fibres, likely due to the mechanical and thermal stresses during recycling, which disrupt crystalline regions.

XRD patterns of all samples displayed the characteristic crystalline peaks of PET at

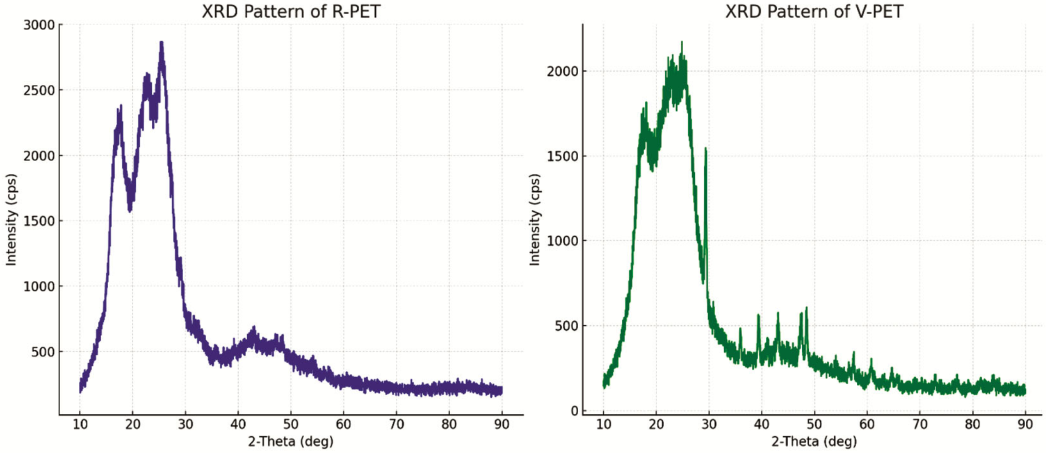

Fig. 5 — The XRD patterns for both rPET and vPET fibres

Table 3 — The average values obtained from mechanical, thermal, electrical, and structural tests

Property	Sample	vPET, Mean	rPET, Mean
Breaking Strength, cN/tex	Ne 28	38.43	26.60
	Ne 40	42.39	26.49
	150 dtex	47.99	44.35
	300 dtex	47.36	35.66
Elongation at Break, %	Ne 28	8.74	12.13
	Ne 40	9.21	12.76
	150 dtex	19.20	21.70
	300 dtex	23.13	25.10
Surface Resistivity, Ω	Ne 28	$>10^{12}$	2.88×10^{9}
	Ne 40	$>10^{12}$	2.01×10^{10}
	150 dtex	$>10^{12}$	3.71×10^{11}
	300 dtex	$>10^{12}$	1.43×10^{10}
Thermal Degradation, Temp, °C		400	370
TGA Residue, %		0.2	0.8
Moisture Loss, TGA, %		0.2	0.5
XRD Crystallinity, %		42.25	30.65

approximately $2\theta = 17.6°$ and $22.6°$, corresponding to the (010) and (100) planes, respectively. The peak positions were consistent across vPET and rPET samples, though peak broadening was observed in rPET, indicating reduced crystallinity. The calculated crystallinity indices revealed significant variation between recycled and virgin PET samples. Virgin polyester in filament form (vPET-F) exhibited the highest crystallinity at 46.3%, followed by virgin staple fibre (vPET-S) at 38.2%. Recycled samples showed lower values: rPET filament (rPET-F) at 33.5% and recycled staple fibre (rPET-S) at 27.8%. These results align with literature noting that thermal and mechanical processing during recycling disrupts the ordered crystalline structure, leading to decreased crystallinity.[25] The lower CI of rPET-S compared to rPET-F may be attributed to the increased surface area and irregular packing in staple fibres, further reducing crystalline alignment.

The recycling process introduces structural irregularities and impurities into rPET fibres, leading to a more disordered structure compared to vPET fibres. This is reflected in the lower intensity and broader peaks in The XRD pattern of r-pet. These findings are consistent with the results obtained in some previous studies in literature[26,27].

Table 3 summarizes the average values obtained from mechanical, thermal, electrical, and structural tests conducted on both vPET and rPET yarns.

Compared to vPET samples, rPET yarns exhibited lower breaking strength but generally higher elongation values. Electrical surface resistivity decreased in rPET, suggesting possible changes in surface properties due to recycling.

Thermogravimetric analysis indicated a slight decrease in thermal degradation temperature for rPET and higher residue and moisture loss, consistent with literature on recycled polymers containing more additives and degraded components. The residual weight of rPET (0.8%) was significantly higher than that of vPET (0.2%), suggesting the presence of non-volatile contaminants or degradation residues retained from previous processing. XRD crystallinity dropped from 42.25% in vPET to 30.65% in rPET, reflecting the structural disorder induced by mechanical recycling. These findings align with observations reported by Radhakrishnan *et al.* (2019)[25], who noted that mechanical recycling often reduces crystallinity and thermal stability while slightly enhancing fibre ductility.

4 Conclusion

The study reveals significant differences in the structural, mechanical, thermal, and conductive properties of rPET and vPET yarns, largely attributable to the effects of the recycling process. rPET yarns demonstrate lower breaking strength and higher elongation compared to vPET yarns, attributed to structural irregularities, shorter molecular chains, and reduced crystallinity introduced during recycling. These factors lead to a more flexible and deformable fibre structure in rPET, but at the cost of reduced stiffness and tensile strength. In contrast, vPET yarns maintain superior mechanical properties due to their higher crystallinity, longer molecular chains, and more stable molecular structures resulting from controlled manufacturing processes.

The surface resistivity results further highlight the functional differences between the yarns. rPET yarns exhibit significantly lower surface resistivity, classifying them as dissipative, while vPET yarns remain insulating. The increased moisture regain in rPET yarns, due to the presence of hygroscopic sites created by structural irregularities, facilitates ionic conduction, thereby lowering surface resistivity. vPET yarns, with their higher crystallinity and lower moisture absorption, retain higher resistivity values.

Thermal analysis via TGA shows that vPET fibres exhibit superior thermal stability, with decomposition starting at higher temperatures and minimal residual weight, indicative of clean thermal decomposition. In contrast, rPET fibres decompose earlier and retain higher residual weight due to non-volatile contaminants introduced during recycling. Additionally, XRD analysis confirms a higher degree of crystallinity in vPET fibres, as evidenced by sharper and more intense peaks, while rPET fibres exhibit broader, less intense peaks, reflecting a higher proportion of amorphous regions.

Finally, these findings underscore the trade-offs inherent in using recycled polyester. While rPET offers advantages such as better conductivity and flexibility due to its amorphous structure, vPET is outperformed by rPET in terms of mechanical strength, thermal stability, and crystallinity. Understanding these differences is critical for tailoring the choice of materials to specific applications, balancing the sustainability benefits of recycling with performance requirements.

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