

Article

Analysis of the Mechanical Behavior of Virgin and Virgin-Recycled Polystyrene

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Abstract

General-purpose polystyrene (GPPS) is widely used in packaging and insulation, although its recyclability poses environmental challenges that require circular economy strategies. The objective of this study was to evaluate the mechanical and tribological behavior of virgin GPPS (100%N), a 50% virgin–50% recycled blend (50N–50R), and 100% recycled GPPS (100%R), processed in Mexico under controlled injection molding conditions. Micro-tensile, flexural, surface roughness, and sliding wear (pin-on-disk) tests were conducted in accordance with ASTM/ANSI standards. The results show that virgin GPPS exhibited the highest strength (micro-tensile: 31.1 MPa; flexural: 87.8 MPa), while the 50N–50R blend maintained comparable tensile strength (27.5 MPa) with greater ductility, making it viable for secondary applications. Recycled GPPS exhibited a significant reduction in strength (micro-tensile: 18.6 MPa; flexural: 41.1 MPa), although with greater deformability. In tribological tests, the coefficients of friction were 0.480 (100%N), 0.128 (50N–50R), and 0.143 (100%R), all with relative errors of less than 4%, confirming statistical validity. Surface roughness analysis showed that the virgin material had the most uniform surface ($R_a = 1.0 \mu\text{m}$), while the blends exhibited greater variation ($R_a \approx 1.2 \mu\text{m}$). In conclusion, although recycled GPPS has limitations compared to virgin material, it retains acceptable mechanical and tribological properties for non-structural applications. These findings support its potential in circular economy strategies in Mexico and provide a framework for countries with similar recycling infrastructure conditions.



Academic Editors: Gang Wei and Marco Rossi

Received: 28 May 2026

Revised: 28 July 2026

Accepted: 3 August 2026

Published: 7 August 2026

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Keywords: polystyrene (PS); recycled material; mechanical properties; tribology

1. Introduction

Today, polymers are essential to the global economy due to their versatility and low cost [1], although their durability poses environmental challenges that require circular economy strategies [2]. General-purpose polystyrene (GPPS), widely used in packaging and insulation, exemplifies this dilemma: indispensable but difficult to recycle [3]. In Europe, recycling rates exceed 40% thanks to strict policies, while in Latin America they are

less than 20%. Mexico occupies a middle ground, with progress in PET and PE, although polystyrene continues to lag behind [4,5].

The future of polystyrene depends on technological innovation, stricter public policies, and changes in consumption patterns [6], making its management a strategic opportunity to transform an environmental problem into a driver of sustainability. Plastic recycling is one of the major global challenges: in 2022, production exceeded 436 million metric tons, with only 9% actually recycled, reflecting the magnitude of the problem and the need for more efficient strategies [7,8].

The scientific literature on recycled polymers has focused primarily on polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET), evaluating their mechanical, thermal, and, in some cases, tribological properties. In contrast, studies on polystyrene have focused mainly on expanded polystyrene (EPS/PSE), with applications in construction and packaging. However, there is little literature on general purpose polystyrene (GPPS), particularly regarding its mechanical and tribological behavior [9–12]. This knowledge gap highlights the need for systematic research on recycled GPPS under standardized conditions, which would allow for the establishment of comparable parameters and expand its application potential within the framework of the circular economy.

Various studies show that mechanical testing of recycled polymers makes a fundamental contribution to knowledge by generating databases on stress, flexural, and wear behavior—properties essential for engineering design. This approach fills a gap not covered by physicochemical studies focused on molecular structure, glass transition temperature, or composition, as these do not predict mechanical performance under real-world loads. Mechanical characterization enables the selection of materials for industrial applications and the evaluation of the technical feasibility of recycling, translating polymer science into practical and sustainable solutions in structural engineering [13–16].

To evaluate the recyclability of general purpose polystyrene (GPPS), microtensile, flexural, and tribological (pin-on-disk) tests [17] were applied to three types of material: 100% virgin (100% N), a 50% virgin–50% recycled blend (50N–50R), and 100% recycled (100% R) under dry conditions for tribological performance [18]. These analyses allow for a comparison of the mechanical and tribological behavior of polystyrene at different levels of recycling, highlighting limitations compared to virgin polymers but also opportunities in secondary applications [19]. The main contribution of this research lies in examining a little-studied polymer such as GPPS through a comprehensive and standardized approach that combines mechanical and tribological properties within a single experimental framework. Unlike previous studies focused on more common polymers (PP, PE, PET) or expanded polystyrene (EPS), this study establishes previously unpublished correlations between mechanical strength and tribological behavior in recycled GPPS, generating scientific evidence that expands its potential for application in non-structural sectors—including packaging, office supplies, light consumer products, signage, furniture, and automotive interior components. In this way, the research not only fills a gap in the literature but also offers an innovative contribution by linking experimental characterization with practical applications within the framework of the circular economy.

2. Materials and Methods

2.1. Materials

For this study, three material formulations were prepared based on the results of micro-hardness tests conducted by A. Guerrero [20]. It is important to note that the new material used was HF 555 crystal polystyrene (GPPS) supplied by RESIRENE (Tlaxcala, México).

The recycled material used in this study is general-purpose clear polystyrene, colored with master batches of various shades. This material was initially processed using cold-

runner injection molding and subsequently ground up for reincorporation. Regarding the processing history of the recycled material, it should be noted that it underwent only one additional reprocessing cycle: it was first processed as virgin material via cold-runner injection molding and, after being ground, was re-injected to produce the test specimens analyzed. Therefore, the 100%R and 50N–50R formulations correspond to polymer with a single reprocessing cycle, which limits the molecular degradation associated with multiple reprocessing cycles.

The new material was supplied in pellet form, while the recycled material was supplied in flake form because it had been ground; subsequently, to produce the samples, it was processed via cold runner injection molding. The molding parameters included barrel zone temperatures of 222 °C (zone 1), 201 °C (zone 2), and 200 °C (zone 3); cold runner injection molding was performed at a pressure equivalent to 25% of the machine's hydraulic system's maximum capacity, which corresponded to approximately a range of 30–50 MPa, according to the manufacturer's specifications. This setting allowed for the production of homogeneous specimens with a shot weight of 87 g; the cycle time was 50 s per shot, and the cooling time was 15 s per cycle. It is important to note that these were the conditions under which the samples were processed for the microtensile, flexural, roughness, and sliding wear tests. The decision to maintain identical conditions is based on the objective of directly comparing the effect of recycled content on mechanical and tribological properties, thereby preventing variations in the process from introducing additional sources of variation. We acknowledge that the viscosity of the melt may vary between formulations and that this could influence the microstructure and the generation of residual stresses; however, by limiting reprocessing to a single cycle, we sought to reduce molecular degradation and ensure homogeneity in the test specimens.

Table 1 below shows the proportions used to prepare the material in the hopper: for the 100% mixture, 10 kg of new material was added; for the 50% mixture, 5 kg of new material and 5 kg of recycled material were used; and for the 0% mixture, 10 kg of recycled material was added to the hopper.

Table 1. Concentrations of material for the preparation of the three samples to be analyzed.

Sample Description	Virgin Material	Recycled Material	Sample No.	Symbols
New	100%	0%	1	100%N
50	50%	50%	2	50N–50R
Recycled	0%	100%	3	100%R

To test the 100%N, 50N–50R, and 100%R samples, they are subjected to microtensile, flexural, roughness, and sliding wear tests in order to determine the loss of their mechanical properties as recycled material is added and to evaluate the feasibility of using material containing 50% recycled content. Table 2 below summarizes the standards used for conducting the tests.

Table 2. Standards used for the mechanical analysis of clear polystyrene.

Test	Standard	Reference
Micro-tensile	ASTM D1708	[21]
Flexural	ASTM D790	[22]
Roughness	ANSI B46.1	[23]
Sliding wear (Pin on disk)	ASTM G99-23	[24]

Note: American Society for Testing and Materials (ASTM).

2.2. Micro-Tensile Testing

Micro-tensile tests were conducted in accordance with ASTM D1708, using micro-dogbone specimens made of virgin general purpose polystyrene (GPPS) and blends containing recycled material (ground GPPS and HIPS), which were obtained through mechanical grinding and subsequent injection molding. The dimensions of the specimens conformed to the standard's specifications, with a total length of 100 mm, a gauge length of 22 mm, a gauge width of 5 mm, and a thickness of 3 mm.

Micro-tensile tests were performed on a Shimadzu MWG-100kN (Nishinokyo-Kuwabaracho, Nakagyo-Ku, Kyoto, Japan) universal testing machine, with a maximum capacity of 100 kN, equipped with mechanical grips and a 1 kN load cell to ensure accuracy for polymeric materials; tensile tests were conducted at a speed of 1 mm/min. Prior to testing, the specimens were conditioned at 23 ± 2 °C and $50 \pm 5\%$ relative humidity, in accordance with ASTM D618 [25], to ensure reproducible conditions.

Ten replicates were performed per condition (100%N, 50N–50R, and 100%R). Force and displacement data were recorded in real time and subsequently processed to obtain maximum strength, elastic modulus, and elongation at break.

2.3. Methodology for Flexural Testing

Flexural tests were conducted in accordance with ASTM D790, using rectangular specimens of virgin general purpose polystyrene (GPPS) and blends with recycled material (ground GPPS and HIPS), obtained through mechanical grinding and subsequent injection molding. The dimensions of the specimens were 100 mm in length, 20 mm in width, and 3.06 mm in thickness. The flexural tests were performed on a Shimadzu MWG-100kN universal testing machine, with a maximum capacity of 100 kN, equipped with mechanical grips and a 1 kN load cell to ensure accuracy for polymeric materials, using a three-point bending configuration with a 48 mm span and a loading rate of 1 mm/min. Ten replicates were performed per condition (100%N, 50N–50R, and 100%R).

2.4. Roughness

The surface roughness of the clear polystyrene specimens was determined in accordance with ANSI B46.1, using a MITUTOYO SURFTTEST-402 (Mitutoyo Corporation, Kawasaki, Japan) roughness tester equipped with a standard probe. Measurements were performed under the following test conditions, as shown in Table 3, to ensure the representativeness of the evaluated surface.

Table 3. Reference parameters used in the roughness tests.

Characteristic	Value
Range	10.0
$\eta \lambda c$	$\times 5$
$\lambda c/L$	0.8

Note: Multiplier factor (η), Cut length (λc), Total length (L).

The test specimens measured $50 \times 50 \times 4$ mm and were pre-cleaned with isopropyl alcohol to remove surface contaminants. Thirty repetitions were performed per condition (100%N, 50N–50R, and 100%R).

The roughness values obtained were processed using the equipment's software, calculating characteristic parameters such as R_a , R_q , and R_z , and were reported as averages and standard deviations for each condition. These results will subsequently be used to correlate the initial surface roughness with the tribological behavior observed in the sliding wear tests (pin-on-disk).

2.5. Sliding Wear (Pin-on-Disk)

Sliding wear tests were conducted in accordance with ASTM G99-23, using circular specimens made of virgin general purpose polystyrene (GPPS) and blends containing recycled material (ground GPPS and HIPS), obtained through mechanical grinding. The specimens measured 30 mm in diameter and 4 mm in thickness. The counter body used was a 6-mm-diameter AISI 52100 steel ball (Hartford Technologies, Inc., Rocky Hill, CT, USA). The test was conducted under dry contact conditions, without the application of lubricant, ensuring direct interaction between the steel ball and the plastic surface [24].

Prior to the wear tests, the specimens were cleaned with isopropyl alcohol to remove surface contaminants. This procedure is common in tribological studies and does not affect the integrity of either general purpose polystyrene (GPPS) or HIPS, ensuring reproducible contact conditions [26].

The tests were performed on an Anton Paar TRB³ tribometer (Anton Paar GmbH, Graz, Austria), configured in linear reciprocating mode with a stroke of 10 mm, until a total distance of 5 m was completed. The applied load was 5 N and the sliding speed was 0.5 cm/s. The equipment has a normal force range of up to 60 N, a friction resolution of 0.06 mN, and a linear travel capacity of up to 60 mm, ensuring precision in the measurement of tribological parameters. Three replicates were performed per condition (100%N, 50N–50R, and 100%R). The friction force and volume loss data were recorded in real time.

This research aims to evaluate the mechanical and tribological behavior of recycled GPPS through tensile, flexural, roughness, and wear tests. While physicochemical tests, such as molecular weight characterization or oxidation state factors that can influence strength, friction, and wear, were not included, the results obtained are valid and allow for the identification of initial trends under controlled laboratory conditions. Future work will complement the analysis with molecular characterization and oxidation studies to establish more comprehensive correlations between chemical degradation and the mechanical–tribological performance of recycled GPPS.

3. Results

3.1. Microtensile Stress

3.1.1. Normality Test Results for Microtensile

The results obtained for the three conditions analyzed (100% N, 50N–50R, and 100% R of transparent polystyrene) showed a good fit to the normal distribution, as shown in Table 4. The Anderson–Darling (AD) statistic values were low (0.170–0.277), and the associated *p*-values (0.572–0.905) confirmed the normality of the data. Consequently, the necessary assumptions for applying parametric statistical methods, such as analysis of variance (ANOVA) and the Tukey test, are met when comparing the mean stresses obtained in the tests.

Table 4. Normality test results and confidence intervals for micro-tensile stresses.

Sample	Mean $\pm$ SD (MPa)	95% CI (MPa)	<i>n</i>	AD	<i>p</i> -Value
100%N	31.1 $\pm$ 5.02	[27.5–34.7]	10	0.277	0.572
50N–50R	27.5 $\pm$ 2.97	[25.4–29.6]	10	0.170	0.905
100%R	18.6 $\pm$ 2.67	[16.7–20.5]	10	0.220	0.773

Note: Standard Deviation (SD) and Confidence intervals (CI) were calculated using Student's *t*-distribution at 95% confidence level for each experimental group.

The normality results indicate that the data is acceptable since the *p*-values are greater than 0.05. Furthermore, the Anderson–Darling results show low values, indicating that the deviations are small.

3.1.2. Statistical Analysis for Microtensile

The results of the ANOVA analysis show that the sample means are different, as shown in Table 5, because the critical F-value = 3.354 ($\alpha = 0.05$) and is exceeded by the calculated F-value = 30, confirming that the recycled material does affect the mechanical property of microstress, specifically the stress; however, it is not possible to determine which means have significant differences among the three groups. The results of the analysis of variance are presented below.

Table 5. Results of the analysis of variance for Microtensile.

Source	DF	SS	MS	F	<i>p</i>
Factor	2	823.6	411.8	30	0.00
Error	27	370.6	13.7		
Total	29	1194.1			

S = 3.705, R-squared = 68.97%, R-squared (adjusted) = 66.67%. Note: Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-statistic (F), *p*-value (*p*), Standard error of the estimate (S).

Using Tukey's test, the sample means and standard deviations were obtained, as presented in Table 4. Subsequently, the means exhibiting statistically significant differences were identified using individual 95% confidence intervals (CI) and a pooled standard deviation of 3.705. Table 6 shows that the first group, consisting of 100%N (31.1 MPa) and the 50N–50R (27.5 MPa) in the same statistical group designated (A), while the 100%R (18.6 MPa) was placed in a separate group designated (B).

Table 6. Aggregation of the average values of the forces obtained from the micro-tensile tested samples.

Sample	<i>n</i>	Mean (MPa)	Grouping
100%N	10	31.1	A
50N–50R	10	27.5	A
100%R	10	18.6	B

Means that do not share a letter are significantly different. The 95% Tukey's simultaneous confidence intervals shown. All pairwise comparisons. Individual confidence level = 98.0%.

This confirms that the 50N–50R samples do not differ significantly from the 100%N sample in terms of the stresses they can withstand before breaking, but there is a clear difference compared to the 100%R sample, as their stress capacity decreases dramatically—by as much as 40%—when compared to the 100%N material.

3.1.3. Stress–Strain Curve for Micro-Tensile Testing

Figure 1 shows that the 100% virgin sample can withstand the highest stress and exhibits the behavior of a rigid polymer; as recycled material is added, this strength decreases. Likewise, we can observe that the 100%N sample has low ductility, and as recycled material is added, its ductility increases; that is, it withstands more deformation before reaching the breaking point, adopting the characteristics of a flexible polymer, as cited by Coreño-Alonso, J., in his research on the structure–property relationship of polymers [27]. The 100% virgin material (100%N) has the highest strength (31.1 MPa) and behaves like a rigid, brittle polymer, with low deformation before fracture. The 50N–50R blend maintains an intermediate strength (27.5 MPa), statistically similar to that of the virgin material, but with greater ductility, which allows it to absorb more energy before breaking and makes it a viable candidate for secondary applications. In contrast, the 100% recycled material (100%R) shows a significant drop in strength (18.6 MPa, a 40% reduction), although it exhibits the greatest deformation capacity, behaving like a flexible

polymer. Overall, the graph shows a progressive transition: from rigid–brittle (100%N), to moderately ductile (50N–50R), to highly ductile but weak (100%R).

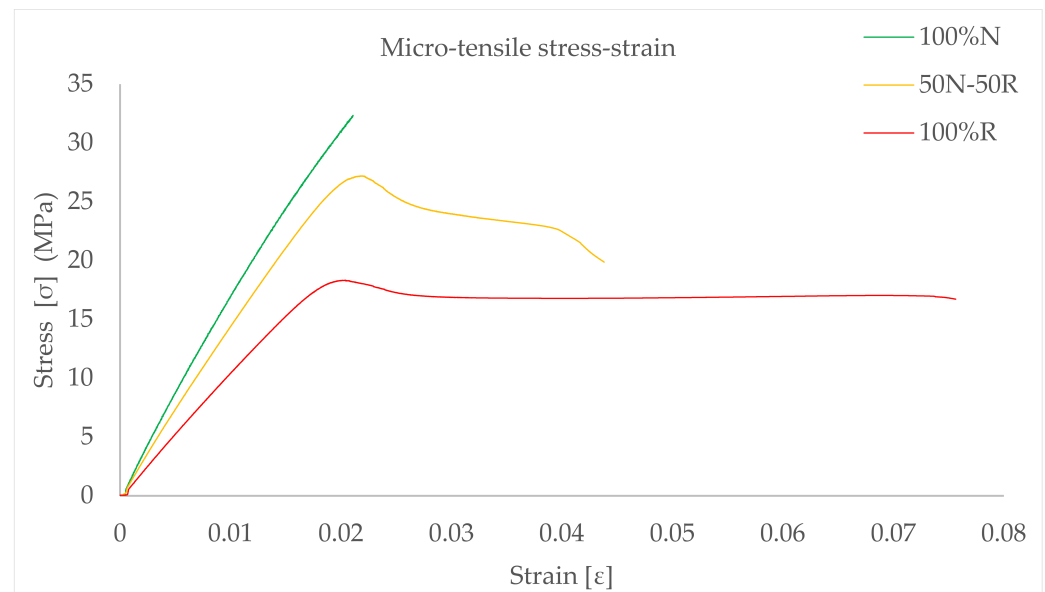


Figure 1. Micro-stress–strain graph.

3.2. Flexural Testing

3.2.1. Normality Test Results for Flexural

Regarding the performance of the samples in the flexural strength test, Table 7 shows that the sample made of 100% R barely exceeds the minimum p value required for the data to be considered normal, thereby allowing the application of subsequent statistical tests to determine whether there is a significant difference between their stress means, with the objective of being able to use samples containing 50N–50R material that show no significant difference compared to the 100%N material.

Table 7. Normality test results and confidence intervals for flexural stresses.

Sample	Mean $\pm$ SD (MPa)	95% CI (MPa)	n	AD	p -Value
100%N	87.8 $\pm$ 2.87	[84.2–91.4]	5	0.221	0.664
50N–50R	59.5 $\pm$ 1.90	[57.1–61.9]	5	0.183	0.816
100%R	41.1 $\pm$ 2.61	[37.9–44.3]	5	0.593	0.055

3.2.2. Statistical Analysis for Flexural

The results of the analysis show that the sample means are different, as shown in Table 8, because the critical F -value = 3.885 ($\alpha = 0.05$) and is exceeded by the calculated $F = 445.49$, indicating which samples differ in these flexural tests and that the recycled material does affect the mechanical flexural properties, specifically the stress; however, it is not possible to determine which means have significant differences among the three groups. The results of the analysis of variance are presented below.

Table 8. Results of the analysis of variance for flexural.

Source	DF	SS	MS	F	p
Factor	2	5525.56	2762.78	445.49	0.00
Error	12	74.42	6.20		
Total	14	5599.98			

$S = 2.490$, R -squared = 98.67%, R -squared (adjusted) = 98.45%.

The Tukey test groups together means that they do not differ significantly; however, it identifies the differences between the means: the 100%N material (87.8 MPa), the 50N–50R (59.5 MPa), and the 100%R (41.1 MPa) do not share any statistical group because their means do present significant differences, as shown in Table 9, with individual 95% confidence intervals for the mean based on a pooled standard deviation of 3.705. This indicates that the stresses experienced by the samples are distinct.

Table 9. Aggregation of the average values of the forces obtained from the flexural tested samples.

Sample	<i>n</i>	Mean (MPa)	Grouping
100%N	5	87.8	A
50N–50R	5	59.5	B
100%R	5	41.1	C

Means that do not share the same letter are significantly different. The 95% Tukey's simultaneous confidence intervals are shown. All pairwise comparisons. Individual confidence level = 97.9%.

3.2.3. Stress–Strain Curve for Flexural Testing

Figure 2 shows the mechanical behavior of three types of crystalline polystyrene (100%N, 50N–50R, 100%R) under bending load. The 100%N specimen exhibits the highest maximum stress (87.8 MPa) with low strain (0.026). The initial slope is steep, reflecting high stiffness. The failure mode is abrupt, characteristic of a brittle material. The 50N–50R sample reaches an intermediate stress (59.5 MPa) with greater strain (0.1097). It exhibits more ductile behavior, with a wider plastic zone and greater elongation capacity before fracture. However, for the 100%R samples, it records the lowest maximum stress (41.1 MPa) but the highest strain (0.187). It behaves as a highly ductile material, with low stiffness and reduced strength, but with the ability to absorb greater deformation than the others before failing.

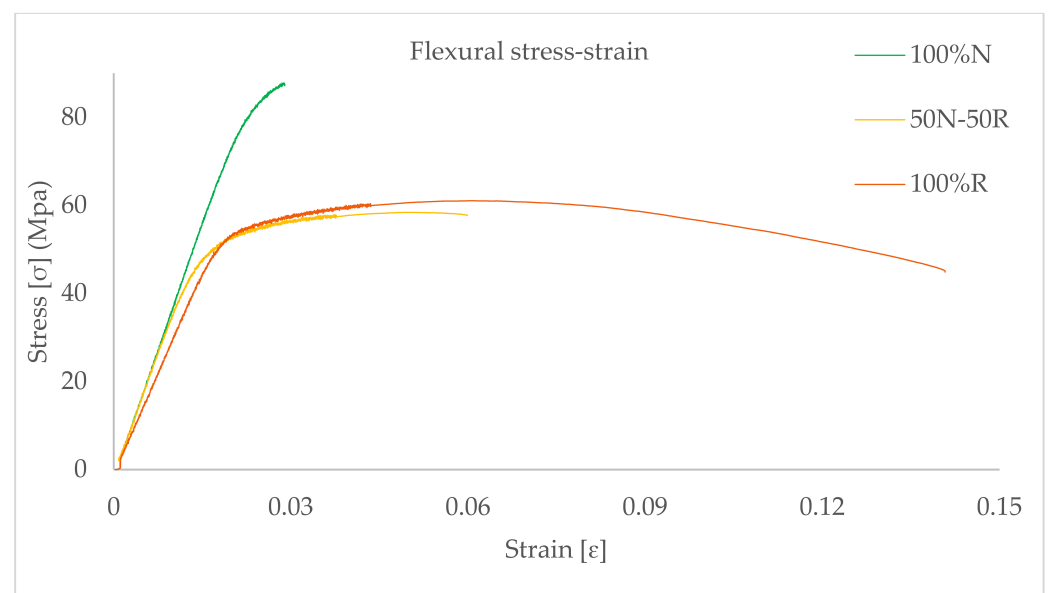


Figure 2. Stress–Strain Curve for Bending.

3.3. Surface Roughness

For each ratio, 30 tests were conducted, yielding average values together with their standard deviations. In addition, 95% confidence intervals were calculated using Student's t-distribution for each experimental group. The results are presented in Table 10, which compares the surface roughness parameters Ra, Rq, and Rz, along with a brief description of the analyzed surface.

Table 10. Surface roughness results for clear polystyrene. All values presented correspond to micrometers (μm).

Sample	Ra $\pm$ SD [IC95%]	Rq $\pm$ SD [IC95%]	Rz $\pm$ SD [IC95%]	Observation
100%N	1.0 $\pm$ 0.23 [0.91–1.09]	1.2 $\pm$ 0.30 [1.09–1.31]	4.6 $\pm$ 0.93 [4.26–4.94]	More uniform surface, lower dispersion, fewer peaks and valleys
50N–50R	1.2 $\pm$ 0.23 [1.11–1.29]	1.5 $\pm$ 0.34 [1.37–1.63]	6.6 $\pm$ 1.48 [6.06–7.14]	Greater variability, presence of higher peaks
100%R	1.2 $\pm$ 0.17 [1.14–1.26]	1.5 $\pm$ 0.21 [1.42–1.58]	6.5 $\pm$ 0.93 [6.16–6.84]	Average roughness similar to 50%, but with lower dispersion

A comparison of surface roughness among the three ratios analyzed (100%N, 50N–50R, and 100%R) reveals differences in homogeneity and dispersion. The new material exhibited the most uniform surface ($R_a = 1.0 \pm 0.23 \mu\text{m}$; $R_q = 1.2 \pm 0.30 \mu\text{m}$; $R_z = 4.6 \pm 0.93 \mu\text{m}$), which suggests better tribological performance due to the lower presence of asperities [15]. The 50N–50R specimens exhibited greater variability ($R_a = 1.2 \pm 0.23 \mu\text{m}$; $R_q = 1.5 \pm 0.34 \mu\text{m}$; $R_z = 6.6 \pm 1.48 \mu\text{m}$), indicating a more irregular surface and consequently influencing the friction results [28]. Finally, the 100%R samples showed values similar to those of the 50N–50R ($R_a = 1.2 \pm 0.17 \mu\text{m}$; $R_q = 1.5 \pm 0.21 \mu\text{m}$; $R_z = 6.5 \pm 0.93 \mu\text{m}$), although with lower dispersion, reflecting a more stable surface despite the exclusive use of recycled polymer [10]. Overall, the three materials are suitable for evaluating tribological wear using the pin-on-disk method, as their roughness parameters fall within ranges appropriate for correlating with friction and material loss [24]. However, it is anticipated that the new material will have more stable performance, followed by the recycled material, while the 50N–50R blend could show greater susceptibility to wear due to the presence of more pronounced asperities.

The ASTM G99-23 standard stipulates that surfaces used in the pin-on-disk test must be prepared in a uniform and reproducible manner, although it does not specify a single roughness value [24]. In experimental practice, tribological studies on polymers report that average roughness values between 0.05 and 1.5 μm (R_a) are acceptable, as they allow for comparable and reproducible results [29]. When roughness exceeds 2 μm , contact between asperities dominates the initial wear, which alters the friction measurement and turns the test into a more abrasive test rather than a controlled sliding test [30]. Therefore, for polymers such as crystal polystyrene, roughness values $\leq 1 \mu\text{m}$ are considered adequate and acceptable, while roughness values greater than 2 μm no longer represent valid conditions for the pin-on-disk method.

3.4. Sliding Wear (Pin-on-Disk)

3.4.1. Normality Test

The results obtained for the three conditions analyzed (100%N, 50%N and 50%R, and 100%R of transparent polystyrene) showed a good fit to the normal distribution, as shown in Table 11. The Anderson–Darling (AD) statistic values were low (0.192–0.281), and the associated p -values confirmed the normality of the data. Consequently, the necessary assumptions for applying parametric statistical methods—such as analysis of variance (ANOVA) and the Tukey test—to compare the means of the wear rates are met. Furthermore, the observed standard deviation was low relative to the differences between the groups, which reinforces the reliability of the results.

Table 11. Normality test results and confidence intervals for the sliding wear tests.

Sample	Mean $\pm$ SD (COF)	95% CI	<i>n</i>	AD	<i>p</i> -Value
100%N	0.480 $\pm$ 0.008	[0.460–0.500]	3	0.192	0.619
50N–50R	0.128 $\pm$ 0.005	[0.120–0.136]	3	0.281	0.323
100%R	0.143 $\pm$ 0.005	[0.135–0.151]	3	0.241	0.445

Note: Coefficient of Friction (COF).

3.4.2. Statistical Analysis for Sliding Wear

The results presented in Table 12 show that the sample means differ significantly, given that the critical F-value (5.14, with $\alpha = 0.05$) is far exceeded by the calculated F-value of 2968.44. This finding confirms highly significant differences among the three groups of expanded polystyrene evaluated. Although the ANOVA demonstrates the existence of these differences, it is not yet possible to specify which means differ from one another. These results confirm that recycling directly affects the tribological properties of the material.

Table 12. Results of analysis of variance (ANOVA).

Source	DF	SS	MS	F	<i>p</i>
Factor	2	0.2378247	0.1189124	2968.44	0
Error	6	0.0002404	0.0000401		
Total	8	0.2380651			

Tukey's test revealed that the virgin polystyrene crystal group differs significantly from the groups containing recycled material, exhibiting a higher friction coefficient associated with wear. In contrast, the 50N–50R and 100%R groups did not show statistical differences between them, indicating that even a partial proportion of recycled material reduces the friction coefficient to levels statistically equivalent to those of fully recycled material. The results presented in Table 13, supported by individual 95% confidence intervals for the mean and a pooled standard deviation of 0.00633, confirm that the incorporation of recycled material clearly and directly affects the wear resistance of polystyrene crystal.

Table 13. Grouping of friction coefficient averages for the tested samples.

Sample	<i>n</i>	COF	Grouping
100%N	3	0.480	A
50N–50R	3	0.128	B
100%R	3	0.143	B

Means that do not share a letter are significantly different. The 95% Tukey's simultaneous confidence intervals are shown. All pairwise comparisons. Individual confidence level = 97.8%.

3.4.3. Friction Coefficient and Wear Rate Curve

Figure 3 shows clear differences in the coefficient of friction among the three groups of crystal polystyrene. The 100%N material exhibited high and stable values (0.480), while the materials containing recycled content (50N–50R% and 100%R) showed significantly lower coefficients (0.128–0.143) that were statistically equivalent to one another. These results indicate that the incorporation of recycled material, even in moderate proportions, immediately reduces friction and stabilizes the tribological behavior of crystal polystyrene.

However, the wear rate results shown in Figure 4 indicate that, on average, the material with the highest wear rate is the 100%R material, followed by the 100%N material, and finally, the material with the lowest wear rate among the three tests is the 50N–50R material.

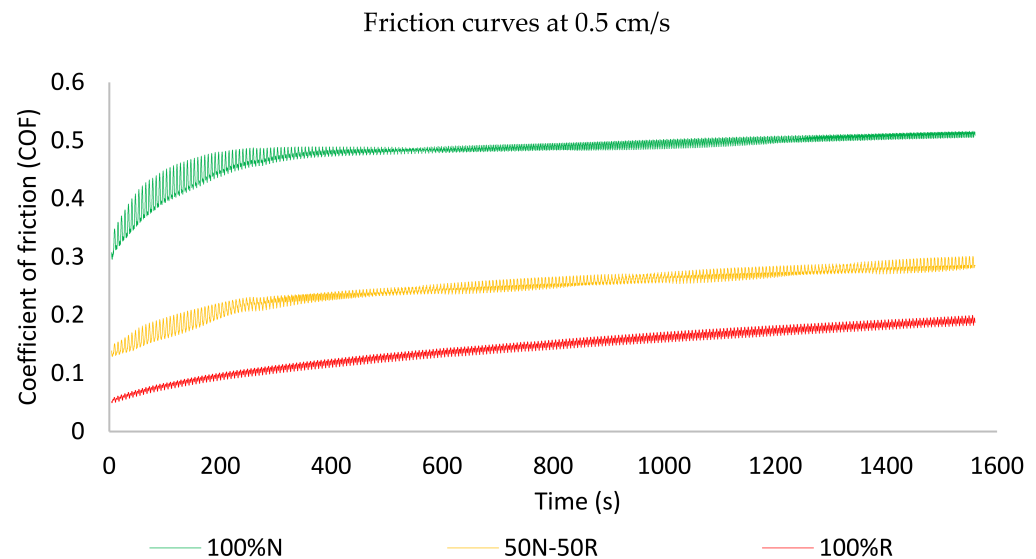


Figure 3. Variation in the coefficient of friction in the tested samples.

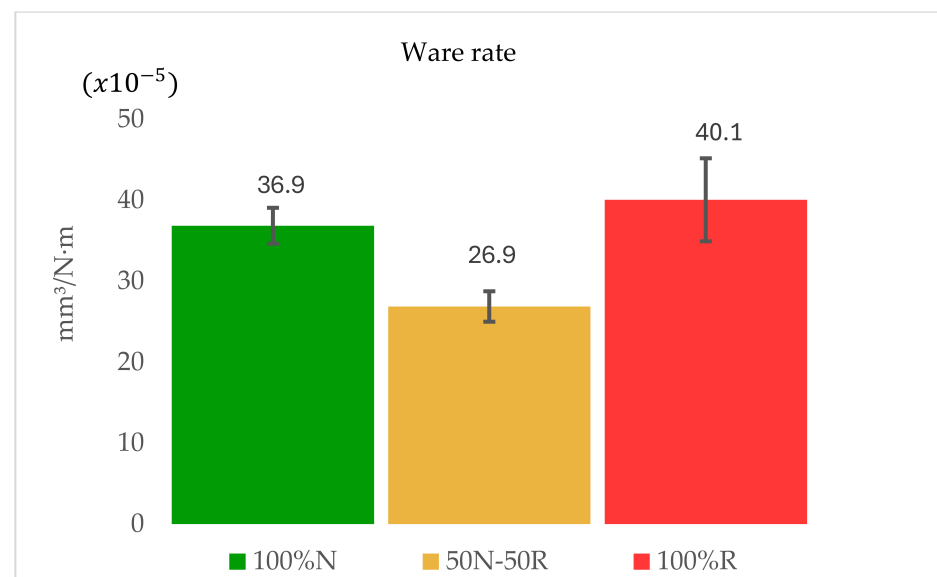


Figure 4. Wear rate of new and recycled clear polystyrene.

The validation of the experimental results was carried out following the procedure described by Shirakov (1985) [31], a methodology that has also been applied in recent studies on friction coefficients in physical–mechanical properties conducted by Pérez, Rigoberto A.; Daquinta, Lázaro A.; Águila [32]. According to the literature, for a 95% confidence level and a small sample size ($n = 3$), the maximum allowable relative error is 4%. In this study, the coefficients of friction obtained for the three conditions of crystalline polystyrene (100%N, 50%N and 50%R, and 100%R) had relative errors of 1.76%, 3.87%, and 3.43%, respectively, all of which were below the established limit. These results, shown in Table 14, confirm that experimental variability remains within acceptable ranges and that the data are statistically valid and reliable, thereby ensuring the accuracy and reproducibility of the tribological conclusions. Furthermore, as noted by Kuehl [33] and Gutiérrez Pulido & De la Vara [34], a small sample size may be acceptable provided it is supported by an adequate confidence level and rigorous control of relative error, thereby ensuring the validity of the experimental results. In addition, tests were conducted at low speeds (0.5 cm/s) in order to obtain reproducible results and avoid excessive heat generation and surface degradation.

Table 14. Results of the relative error applied for the validation of the experimental data.

Sample	n1	n2	n3	Mean	Std. Dev.	Relative Error
100%N	0.489	0.481	0.472	0.480	0.008	1.76%
50N–50R	0.134	0.125	0.127	0.128	0.004	3.87%
100%R	0.139	0.148	0.142	0.143	0.004	3.43%

The tribological tests were conducted in accordance with ASTM G99, using three replicates per condition. Although the standard does not specify a mandatory minimum number of samples, this sample size meets statistical validation criteria and allows for reliable results. However, the limited number of samples restricts statistical power and the ability to extrapolate to industrial scenarios; therefore, the findings should be interpreted as initial trends. Future work will include increasing the number of replicates and supplementing the analyses with confidence intervals to strengthen the applicability of the results at an industrial scale.

3.4.4. Optical Microscopy

Microscopic images of the worn surfaces reveal clear differences among the three types of crystalline polystyrene analyzed. In Figure 5a, corresponding to the 100% virgin material (100%N), adhesive wear is observed at the edges of the indentation, evidenced by clusters of material accumulated on the sides of the pin's path (orange arrows). The grooves are more homogeneous and of relatively constant dimensions (292–324 μm), reflecting a uniform surface texture consistent with the higher wear resistance recorded in the tribological tests. In Figure 5b, corresponding to the 50N–50R blend, the blue arrows point to grooves aligned with the direction of the pin's movement, resulting from harder particles that caused abrasive wear. These particles, derived from the recycled material, are visible as white dots (orange arrows), and the measurements (285–312 μm) show intermediate variability with moderate irregularities, which is consistent with the significant reduction in wear resistance. Finally, in Figure 5c, corresponding to the 100% recycled material (100%R), a more pronounced indentation and wider, more dispersed grooves (310–335 μm) are visible, associated with a heterogeneous microstructure. Although some grooves correspond to surface irregularities and were not in direct contact with the pin (blue arrows), white particles are visible within the indentation, indicating a lack of homogeneity in the recycled polymer matrix. Taken together, the images confirm that the incorporation of recycled material alters the surface uniformity of crystal polystyrene, promotes adhesive and abrasive wear mechanisms, and explains the decrease in wear resistance identified in the pin-on-disk tests.

The statistical analysis performed on groove width and wear rate reveals a strong quantitative relationship between the two variables. The values obtained for the three conditions shown in Table 15 were subjected to a Pearson correlation analysis, yielding a coefficient of $r = 0.85$ ($p < 0.01$), which indicates a strong positive correlation. The coefficient of determination was $R^2 = 0.73$, showing that approximately 73% of the variability in the wear rate can be directly explained by scratch width.

Figure 6 presents the scatter plot with a linear trend line, where it is clearly observed that an increase in tread width is associated with an increase in the wear rate. These results confirm that tread width is a reliable quantitative indicator of wear resistance, and that the presence of recycled material leads to wider treads and, consequently, higher wear rates.

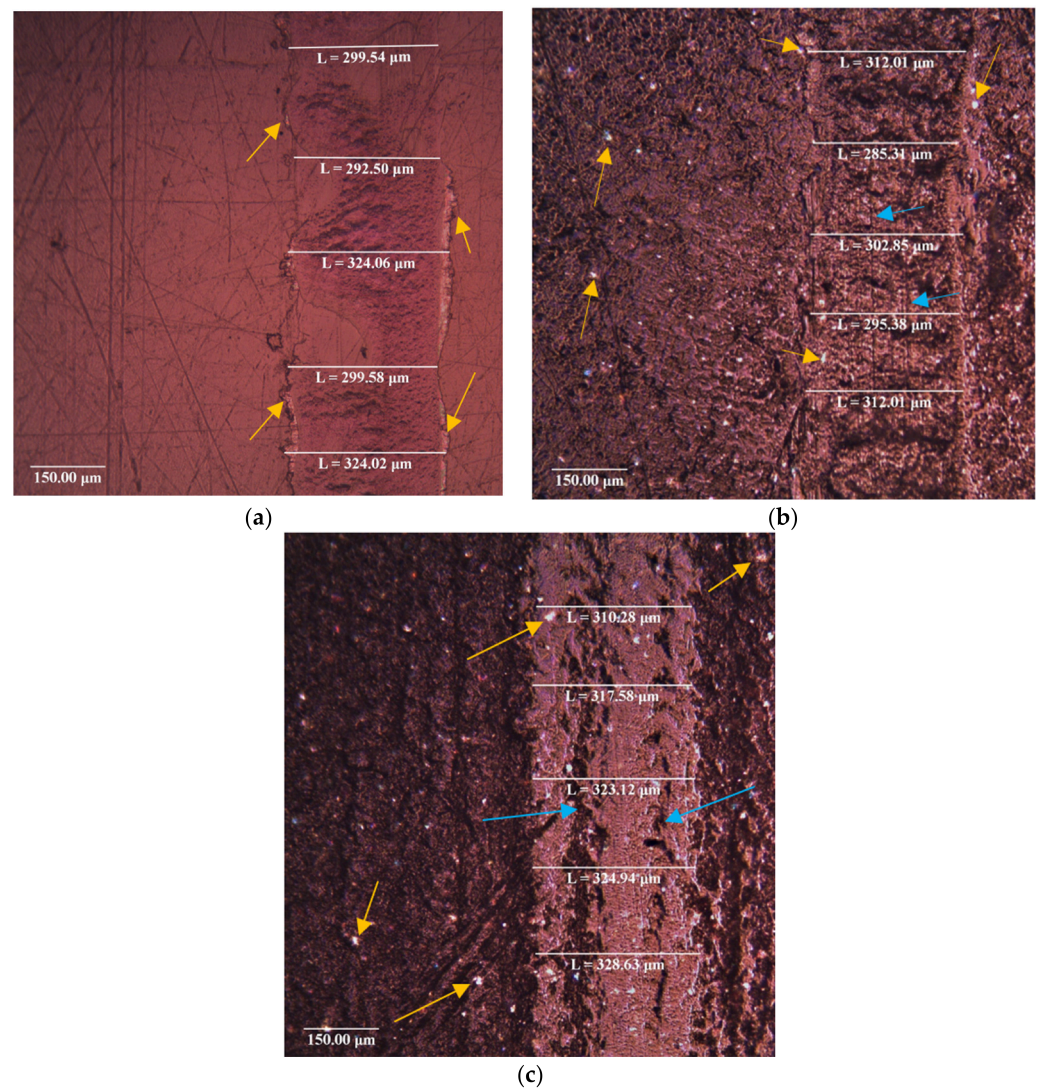


Figure 5. Wear marks caused by sliding (pin-on-disk) for material: (a) 100%N, (b) 50N–50R, and finally material (c) 100%R.

Table 15. Tread width and wear rate values for different sample compositions.

Sample	Wear Track Width (μm)	Wear Rate (10 ^{−6}) (mm ³ /Nm)
	Variable X	Variable Y
100%N	307.94	384.75
	325.85	324.71
	329.09	396.37
50N–50R	301.51	260.61
	286.18	304.79
	278.83	241.03
100%R	320.91	333.01
	310.54	367.52
	355.91	501.45

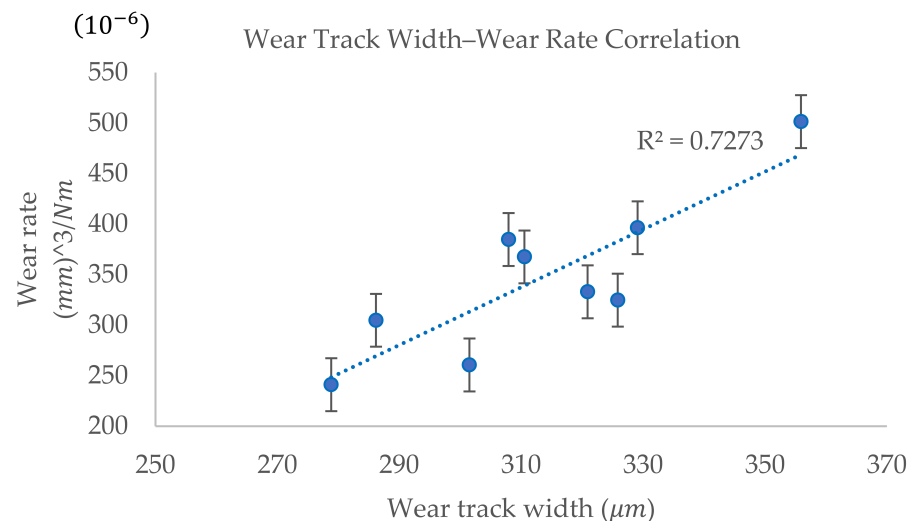


Figure 6. Wear Track Width–Wear Rate Correlation.

4. Conclusions

Analysis of polystyrene (GPPS) with different proportions of recycled material confirms that recycling this polymer is technically feasible and offers distinct performance profiles with technical and environmental implications.

The 50N–50R blend: Maintains tensile strength close to virgin material (27.5 vs. 31.1 MPa), improves ductility, and shows the lowest wear rate ($26.9 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$). Although flexural strength decreases (59.5 vs. 87.8 MPa), its ability to deform before fracturing makes it less brittle. The heterogeneous microstructure acts as a barrier against wear.

The 100% virgin polystyrene: Retains the highest mechanical strength but with lower deformability and higher friction. Tribologically, it exhibited adhesive wear with homogeneous grooves (292–324 μm), confirming that high strength does not necessarily mean better wear performance.

The 100% recycled polystyrene: Shows the greatest reduction in strength (18.6 MPa in tensile and 41.1 MPa in flexural), but compensates with higher ductility and energy absorption. Tribologically, it exhibited wider and more dispersed grooves (310–335 μm), linked to lower wear resistance. Statistical analysis confirmed a strong correlation between groove width and wear rate ($r = 0.85$, $R^2 = 0.73$).

In conclusion, there is no linear relationship between mechanical strength and tribological behavior: the virgin material, although stronger, exhibited higher friction; the 50N–50R blend achieved the best balance; and the 100% recycled material demonstrated that reduced strength is accompanied by greater variability in wear. This study was conducted under controlled laboratory conditions, with a single reprocessing cycle and standardized tests (ASTM/ANSI), without considering multiple reprocessing cycles, thermal variations, prolonged aging, or environmental conditions. Therefore, the findings should be interpreted as initial trends with experimental and comparative scope, applicable to the design of materials for non-structural components, packaging, and consumer goods. Future research should expand the scope through testing under diverse environmental conditions and validation in industrial settings, thereby strengthening the transition toward a circular economy and enabling technology transfer on a larger scale.

Author Contributions: Investigation, data curation, writing—original draft preparation, A.G.-B.; Review, N.L.-P.; Conceptualization, N.L.-P., M.A.D.-R., E.D.G.-B., L.G.V., A.L.-V. and D.S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Consejo Mexiquense de Ciencia y Tecnología (COMECyT) under the program “Investigadoras e Investigadores Promoción 2025” registered with folio EESP2024-0126.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: Laboratorio de Estudios, Modificación y Aplicación de Superficies (LEMAS)-Universidad Politécnica del Valle de México in the project CIR/0022/2022 of the program “Investigadoras e Investigadores por México” of SECIHTI.

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

References

1. Mandatory Recycled Content—EU Packaging Directive. Available online: <https://plasticseurope.org/sustainability/circularity/recycling/mandatory-recycled-content/> (accessed on 26 July 2026).
2. European Environment Agency. Waste Recycling. Available online: <https://www.eea.europa.eu/en/europe-environment-2025/thematic-briefings/circular-economy-and-other-enablers-of-transformative-change/waste-recycling> (accessed on 26 July 2026).
3. Singh, A.; Chauhan, A.; Gaur, R. A Comprehensive Review on the Synthesis, Properties, Environmental Impacts, and Chemiluminescence Applications of Polystyrene (PS). *Discov. Chem.* **2025**, *2*, 47. [CrossRef]
4. Nueva Economía del Plástico en México. Available online: <https://anipac.org.mx/wp-content/uploads/2023/12/4to-Informe-AN-VERSION-FINAL.pdf> (accessed on 26 July 2026).
5. Reciclaje de Envases Plásticos En México. Alcanza Récord Histórico En 2025. Available online: <https://ambienteplastico.com/mexico-reciclaje-envases-plasticos-2025/> (accessed on 26 July 2026).
6. México Mercado de Reciclaje de Residuos Plásticos Tamaño, Participación, Tendencias y Pronóstico por Tratamiento, Material, Aplicación, Proceso de Reciclaje, y Región, 2026–2034. Available online: <https://www.imarcgroup.com/report/es/mexico-waste-plastic-recycling-market> (accessed on 26 July 2026).
7. Houssini, K.; Li, J.; Tan, Q. Complexities of the Global Plastics Supply Chain Revealed in a Trade-Linked Material Flow Analysis. *Commun. Earth Environ.* **2025**, *6*, 257. [CrossRef]
8. Jiang, X.; Bateer, B. A Systematic Review of Plastic Recycling: Technology, Environmental Impact and Economic Evaluation. *Waste Manag. Res.* **2025**, *43*, 1159–1178. [CrossRef] [PubMed]
9. Jamnongkan, T.; Intraramongkol, N.; Samoechip, W.; Potiyaraj, P.; Mongkholrattanasit, R.; Jamnongkan, P.; Wongwachirakorn, P.; Sugimoto, M.; Ito, H.; Huang, C.-F. Towards a Circular Economy: Study of the Mechanical, Thermal, and Electrical Properties of Recycled Polypropylene and Their Composite Materials. *Polymers* **2022**, *14*, 5482. [CrossRef] [PubMed]
10. Alejo-Martínez, S.; Figueroa-López, U.; Guevara-Morales, A. Tribological Performance of High-Density Polyethylene (HDPE) and Recycled Polyvinyl Butyral (PVB) Blends During Pin-on-Disk Tests. *Polymers* **2025**, *17*, 1512. [CrossRef] [PubMed]
11. Shah, R.; Marussich, K.; Kabir, M.H.; Liang, H. Tribological Applications of Recycled and Waste Materials: A Review of Recent Advances and Future Directions. *Lubricants* **2026**, *14*, 104. [CrossRef]
12. Momanyi, J.; Herzog, M.; Muchiri, P. Analysis of Thermomechanical Properties of Selected Class of Recycled Thermoplastic Materials Based on Their Applications. *Recycling* **2019**, *4*, 33. [CrossRef]
13. Acharya, P.; Ebrahimian, H.; Moustafa, M.A. Behavior Study of Commercial Polyurea under Monotonic, Rate Dependent, Cyclic, and Fatigue Tensile Loading for Potential Structural Applications. *Polymers* **2022**, *14*, 1878. [CrossRef] [PubMed]
14. Galina, D.M.; Garcia, D.P.; de Souza, G.G. Caracterización de las propiedades mecánicas de los cuerpos de prueba ABS confeccionados con diferentes parámetros de extrusión vía impresión 3D. *Rev. Iberoam. Polímeros* **2016**, *17*, 303–309.
15. Popescu, D.; Zapciu, A.; Amza, C.; Baci, F.; Marinescu, R. FDM Process Parameters Influence over the Mechanical Properties of Polymer Specimens: A Review. *Polym. Test.* **2018**, *69*, 157–166. [CrossRef]
16. Fernández Rubiano, J.L.; Silva Pérez, M.A.; Valero Barrera, O.A.; Orozco, W.; Quesada, F.; Diaz, M.Á.; Gaviria, L.A. Manejo de Los Materiales Plásticos Reciclados y Mejoramiento de Sus Propiedades. *Univ. Antonio Nariño* **2011**, *1*, 52–60.
17. Di Puccio, F.; Di Pietro, A.; Mattei, L. Pin-on-Plate vs. Pin-on-Disk Wear Tests: Theoretical and Numerical Observations on the Initial Transient Phase. *Lubricants* **2024**, *12*, 134. [CrossRef]
18. Birleanu, C.; Udriou, R.; Cioaza, M.; Bere, P.; Pustan, M. Basalt vs. Glass Fiber-Reinforced Polymers: A Statistical Comparison of Tribological Performance Under Dry Sliding Conditions. *J. Compos. Sci.* **2025**, *9*, 444. [CrossRef]

19. Nagoriya, H.; Arora, G. Pin-On-Disk Computational Analysis: A Powerful Tool for Characterizing the Mechanical Properties of Polymers and Polymer Composites. In *Recent Advances in Mechanical Engineering, Volume 1*; Raghavendra, G., Deepak, B.B.V.L., Gupta, M., Eds.; Lecture Notes in Mechanical Engineering; Springer Nature: Singapore, 2024; pp. 199–214.
20. Guerrero Basilio, A.; Sánchez Huitron, D.; Sánchez Huerta, D.; López Perrusquia, N.; Doñu Ruiz, M.A.; Juanico Lorán, J.A.; López Velázquez, A.; Cortes Suarez, V.J. Optimización de una mezcla polimérica utilizando materiales de residuos-nuevos para la industria manufacturera. *Científica* **2024**, *28*, 1–10. [[CrossRef](#)]
21. *ASTM D1708-18*; Standard Test Method for Tensile Properties of Plastics by Use of Microtensile Specimens. ASTM International: West Conshohocken, PA, USA, 2018. [[CrossRef](#)]
22. *ASTM D790-17*; Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. ASTM International: West Conshohocken, PA, USA, 2017. [[CrossRef](#)]
23. *ASME B46.1-2019*; Surface Texture (Surface Roughness, Waviness, and Lay). ASME: New York, NY, USA, 2019.
24. *ASTM G99-23*; Standard Test Method for Wear and Friction Testing with a Pin-on-Disk or Ball-on-Disk Apparatus. ASTM International: West Conshohocken, PA, USA, 2023. [[CrossRef](#)]
25. *ASTM D618-21*; Practice for Conditioning Plastics for Testing. ASTM International: West Conshohocken, PA, USA, 2021. [[CrossRef](#)]
26. Parodo, G.; Moffa, G.; Silvestri, A.; Sorrentino, L.; Testa, G.; Turchetta, S. Influence of Surface Treatments on the Pull-Off Performance of Adhesively Bonded Polylactic Acid (PLA) Specimens Manufactured by Fused Deposition Modeling (FDM). *Materials* **2025**, *18*, 3965. [[CrossRef](#)] [[PubMed](#)]
27. Méndez-Bautista, M.T.; Coreño-Alonso, J. Relación Estructura-Propiedades de Polímeros. *Educ. Quím.* **2018**, *21*, 291–299. [[CrossRef](#)]
28. Kallewaard, E.V.; González, R.H.A.; Vivancos, C.J. Modelos Para La Predicción de La Rugosidad Superficial En Procesos de Mecanizado Con Arranque de Viruta: Revisión bibliografica. *Sci. Tech.* **2006**, *XII*, 200–206.
29. Myshkin, N.K.; Petrokovets, M.I.; Kovalev, A.V. Tribology of Polymers: Adhesion, Friction, Wear, and Mass-Transfer. *Tribol. Int.* **2005**, *38*, 910–921. [[CrossRef](#)]
30. Jia, B.-B.; Li, T.-S.; Liu, X.-J.; Cong, P.-H. Tribological Behaviors of Several Polymer–Polymer Sliding Combinations under Dry Friction and Oil-Lubricated Conditions. *Wear* **2007**, *262*, 1353–1359. [[CrossRef](#)]
31. Shirakov, V.P. *Análisis Experimentales (Diseño de Experimentos)*; Manual de Hilandería in Moscow: Moscú, Russia, 1985; pp. 392–394.
32. Pérez Reyes, R.A.; Daquinta Gradaille, L.A.; Águila Gómez, J. Evaluación de propiedades físico-mecánicas de tallos de caña de azúcar. *Univ. Cienc.* **2023**, *12*, 81–94. [[CrossRef](#)]
33. Kuehl, R.O. *Diseño de Experimentos: Principios Estadísticos de Diseño y Análisis de Investigación*, 2nd ed.; Thomson Learning: Mexico City, Mexico, 2001.
34. Pulido Gutiérrez, H.; De la Vara Salazar, R. *Análisis y Diseño de Experimentos*, 2nd ed.; McGrawHill: Mexico City, Mexico, 2008.

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