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Literature Review

Tensile and Impact Properties of Mechanically Recycled Polypropylene: A Structured Literature Review

Propiedades de Tracción e Impacto del Polipropileno Reciclado Mecánicamente: una Revisión Bibliográfica Estructurada

Roger Alejandro Del Barco Valdivia[1]. Elizabeth Katherine Aigaje Espinosa[2]

[1]. Professor and Researcher. Universidad Privada del Valle. Cochabamba. Bolivia. rdelbarcov@univalle.edu
[2]. PhD Candidate. The Pennsylvania State University. Pennsylvania. United States. eka5489@psu.edu

ABSTRACT

This literature review aimed to analyze the mechanical behavior of recycled polypropylene (PP), with a specific focus on tensile and impact performance. A structured search was conducted using Google Scholar, selecting eight scientific articles published between 2017 and 2025 that met inclusion criteria such as full-text availability, focus on mechanical recycling, and reporting of key mechanical properties. The selected studies were analyzed and compared based on material composition, additive use, and number of recycling cycles. The results showed that tensile strength was generally retained, with minimal reduction in some cases, especially when fillers such as talc were used. However, impact resistance decreased significantly with increasing recycled content, particularly in the absence of elastomeric modifiers. Differences in feedstock origin, test protocols, and additive strategies were identified as key sources of variability. Despite these challenges, promising approaches were found, including the use of tailored additive systems, closed-loop recycling strategies, and advances in preprocessing technologies. It is concluded that recycled PP can be a technically viable material for various applications, particularly when combined with targeted additives and supported by standardized characterization methods.

Keywords: Recycled polypropylene. Mechanical recycling. Tensile strength. Impact resistance. Mechanical properties.

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RESUMEN

Esta revisión bibliográfica tuvo como objetivo analizar el comportamiento mecánico del polipropileno reciclado (PP), con un enfoque específico en el rendimiento a tracción e impacto. Se realizó una búsqueda estructurada utilizando Google Scholar, seleccionando ocho artículos científicos publicados entre 2017 y 2025 que cumplían con los criterios de inclusión, tales como disponibilidad de texto completo, enfoque en reciclaje mecánico e informe de propiedades mecánicas clave. Los estudios seleccionados fueron analizados y comparados en base a la composición del material, el uso de aditivos y el número de ciclos de reciclaje. Los resultados mostraron que la resistencia a la tracción generalmente se mantenía, con una reducción mínima en algunos casos, especialmente cuando se utilizaban rellenos como el talco. Sin embargo, la resistencia al impacto disminuyó significativamente con el aumento del contenido reciclado, particularmente en ausencia de modificadores elastoméricos.

Se identificaron diferencias en el origen de las materias primas, los protocolos de prueba y las estrategias de aditivos como fuentes clave de variabilidad. A pesar de estos desafíos, se encontraron enfoques prometedores, incluyendo el uso de sistemas de aditivos a medida, estrategias de reciclaje en ciclo cerrado y avances en tecnologías de preprocesamiento. Se concluye que el PP reciclado puede ser un material técnicamente viable para diversas aplicaciones, particularmente cuando se combina con aditivos específicos y se apoya en métodos de caracterización estandarizados.

Palabras clave: Polipropileno reciclado. Reciclaje mecánico. Resistencia a la tracción. Resistencia al impacto. Propiedades mecánicas.

1. INTRODUCTION

The global increase in plastic waste has driven the scientific and industrial community to seek sustainable alternatives for its management and reuse. Among the most widely studied and applied strategies are chemical and mechanical recycling, which allow plastic materials to be reintroduced into the production cycle, helping to reduce environmental impact and support circular economy models.

Global plastic production has experienced extraordinary growth, increasing from 2 million metric tons (Mt) in 1950 to 380 Mt in 2015, with a compound annual growth rate (CAGR) of 8.4% (Geyer et al., 2017), polypropylene (PP) alone represents about 21% of all non-fiber plastics manufactured. Given its extensive use in sectors like packaging and consumer goods, the development of efficient recycling strategies for PP is particularly crucial to reduce plastic waste and support circular economy initiatives.

Chemical recycling involves breaking down polymers into their monomers or other valuable chemicals through pyrolysis, solvolysis, or depolymerization processes. This route offers the advantage of regenerating high-quality plastics even from mixed or contaminated waste. However, it remains economically and technically complex, which limits its large-scale adoption (Achilias et al., 2007). In contrast, mechanical recycling (Figure N° 1) is more widely used due to its lower cost and simplicity. It consists of physically processing the material—by grinding, washing, and remelting—without altering its chemical structure (Schyns & Shaver, 2021).

Despite its advantages, mechanical recycling poses significant challenges, especially regarding the degradation of mechanical properties with each recycling cycle and the reduced performance of materials contaminated with other polymers. Polyethylene (PE) and polypropylene (PP), which are among the most used and discarded thermoplastics worldwide, have been the subject of extensive mechanical recycling research. Studies by Meran et al., 2008 and Aurrekoetxea et al., 2001 demonstrated that while the mechanical recycling of PP is feasible, it often results in reduced tensile strength, impact resistance, and elongation at break, particularly after multiple processing cycles.

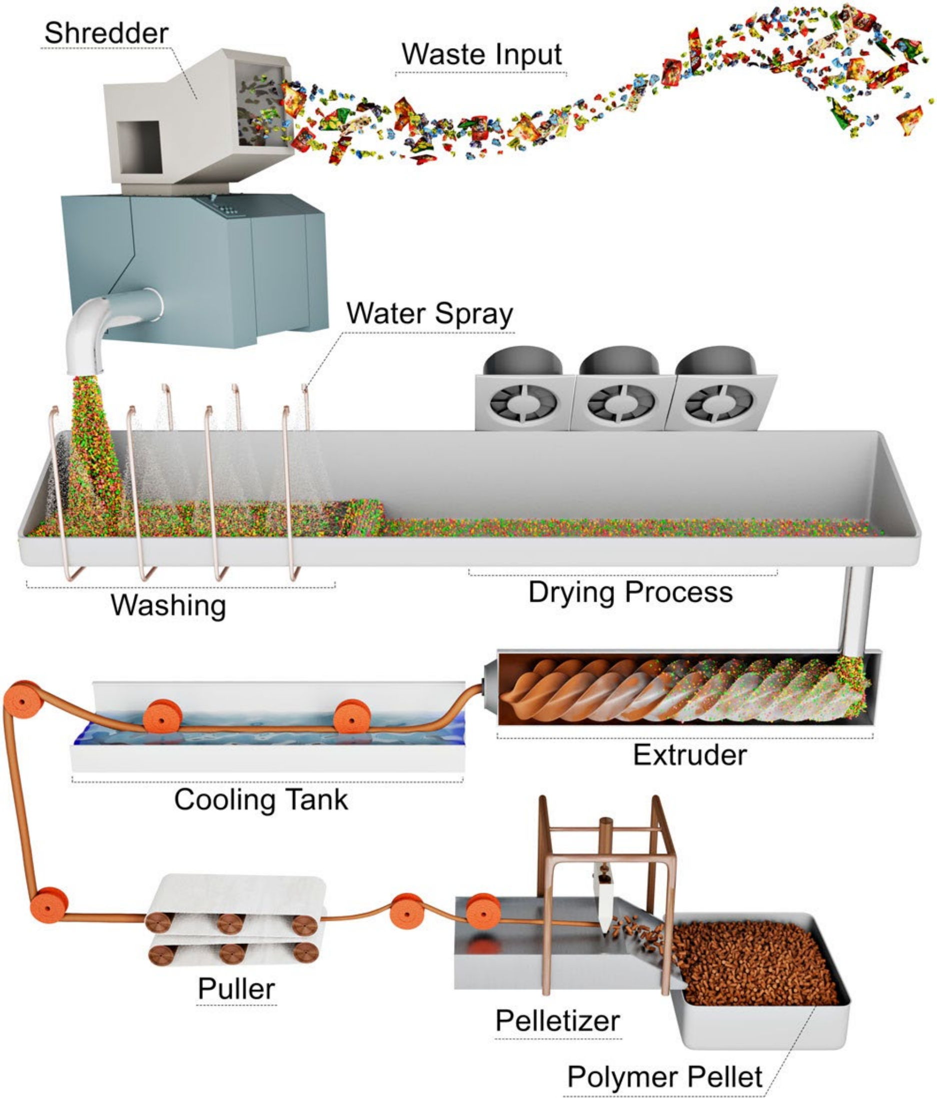

Figure 1. Schematic representation of mechanical recycling. *Source: Reprinted from "Plastic Recycling: Challenges and opportunities", by* (Sambyal *et al*., 2025). *Licensed under CC BY 4.0.*

Nevertheless, there is also evidence that certain properties—such as elastic modulus and crystallization rate—can improve under controlled recycling conditions, especially with the use of fillers and additives. These findings suggest that while mechanical recycling alone may not fully restore the performance of virgin Polypropylene, the combination of recycling strategies with formulation optimization could make recycled PP a viable alternative in many applications.

The objective of this literature review is to analyze and compare the mechanical and thermal behavior of recycled PP, with a particular focus on tensile and impact resistance, as well as exploring how different recycling strategies and material compositions affect these properties. By synthesizing the findings of recent studies, this review aims to identify the key factors influencing recycled PP performance, current limitations, and future research opportunities that could support its broader industrial use.

2. METHODOLOGY

This review is based on a structured literature search conducted in Google Scholar between March and April 2025. The goal was to identify recent studies focused on the mechanical properties of recycled polypropylene (PP), particularly under mechanical recycling conditions.

Although not all selected studies report both tensile strength and impact resistance, each of these properties provides complementary insights into the mechanical performance of recycled polypropylene. Tensile strength reflects the material's ability to withstand static loads, while impact resistance indicates its behavior under dynamic or sudden forces. Including studies that focus on either property allows for a broader understanding of the material's suitability for different applications.

The following Boolean search string was used:

- intitle:polypropylene AND ("mechanical recycling" OR "secondary recycling") AND ("tensile strength" OR "impact resistance") -fiber -reinforced.

To ensure the relevance and timeliness of the data, only studies published between 2017 and 2025 were considered. This search yielded approximately 74 results, which were individually reviewed by examining the titles, abstracts, and, when necessary, the full text, applying the following inclusion criteria:

- Original research articles, review papers, or relevant conference proceedings.
- Explicit focus on the mechanical recycling of polypropylene (excluding chemical recycling).
- Reporting at least one mechanical property: tensile strength and/or impact resistance.
- Written in English.

Due to strict inclusion criteria and focus on recent literature, only eight articles met the selection standards, including one conference paper. Each study was reviewed to look for key details such as material type, additive content, number of recycling cycles and quantitative results from mechanical tests. The articles selected and their key data are summarized in Table 1, which is presented in the following section

This selection strategy supports a focused and current overview of recent advances in recycled PP performance, highlighting both technical progress and persistent challenges in the field.

3. BODY

3.1 State of the Art

Polypropylene (PP) is one of the most used thermoplastics worldwide, found in packaging, automotive parts, consumer goods, textiles, and countless single-use products. The high demand and short lifespan of many PP-based items have led to growing concerns over plastic waste accumulation. In response, mechanical recycling has emerged as a practical and scalable strategy to reintroduce PP into the production cycle. However, questions remain regarding the mechanical, thermal, and structural integrity of recycled PP, especially when compared to its virgin counterpart.

Recent studies provide encouraging evidence that recycled PP can maintain several key properties under certain conditions. For instance, tensile strength, which is critical for structural applications, tends to remain relatively stable even at high recycled content. In one study (Barbosa *et al*., 2017), 100% virgin PP showed a yield strength of 21.65 MPa, while 100% recycled PP presented 20.83 MPa—only a 3.87% reduction. Similar findings were reported by another work (Arese *et al*., 2025), where virgin PP reached 19.5 MPa and recycled samples achieved 17.3 MPa, marking a loss of around 11%. These results suggest that from a purely tensile perspective, recycled PP could remain viable for load-bearing components in certain contexts.

However, impact resistance tells a very different story. In the same study (Barbosa *et al*., 2017) impact strength dropped from 49.5 kJ/m² in virgin PP to just 6.7 kJ/m² in fully recycled samples—an 86% decrease in toughness. This pattern was echoed across several articles (Barbosa et al., 2017, 2020; Domingues *et al.*, 2020) confirming that brittleness increases significantly with the addition of recycled content, especially when no modifiers are used. In structural or dynamic applications where sudden forces are expected, this decline could render recycled PP unsuitable unless its properties are enhanced through additives.

Indeed, one of the major themes across the literature is the strategic use of fillers and modifiers to restore or even improve certain properties of recycled PP. Talc, for example, has been shown to increase rigidity and thermal stability. In a study using PP blends with 30% talc, the recycled material maintained tensile and thermal properties comparable to the virgin control, even after undergoing artificial thermal aging (Arese *et al*., 2025). However, this benefit comes with trade-offs: the same study reported increased brittleness at lower temperatures due to talc's tendency to reduce impact resistance.

Elastomers, on the other hand, offer the opposite effect. In a study by Matei *et al.* (2017) recycled PP initially showed a tensile strength of 2.6 MPa, and adding elastomeric modifiers boosted the strength up to 12 MPa.. These modifiers also enhanced impact resistance, making them suitable for applications requiring ductility and toughness. Yet, their use may reduce stiffness or thermal resistance, and their compatibility with different PP matrices varies across formulations.

Feedstock variability represents another critical issue. Unlike virgin PP, which is typically well-characterized and consistent, recycled PP can come from various sources—industrial scraps, household packaging, multi-layer products, and more. One study (Domingues *et al.*, 2020) using Nescafé® coffee capsule waste, reported a tensile strength of 30.2 MPa and impact resistance of 102 J/m³, indicating that single-source, post-consumer recycled PP can still yield excellent performance. However, such consistency is not guaranteed across mixed or contaminated streams, and many researchers acknowledge that feedstock composition is often poorly documented in published studies.

A comparative summary of tensile and impact performance from selected recent studies is presented in Table 1. This table highlights both the preservation and the deterioration of key mechanical properties across different recycling conditions, formulations, and testing approaches.

Table 1. Summary of mechanical properties and experimental conditions from selected studies.

Article	Material Type	Tensile Strength (MPa)	Impact Resistance *	Key Observations
(Arese *et al*., 2025)	Virgin PP (12% talc)	20	39,2 kJ/m²	Recycled PP is slightly weaker. Talc improves tensile strength but reduces impact resistance.
	Recycled PP (12% talc)	17	41,5 kJ/m²	
	Virgin PP (30% talc)	26	4,4 kJ/m²	
	Recycled PP (30% talc)	24	4,1 kJ/m²	
(Barbosa et al., 2017)	100 % virgin PP	22	49,5 kJ/m²	Recycling causes minor tensile loss (−3.87%), but impact drops by 86%.
	70% Virgin PP + 30% Recycled PP	21	13,3 kJ/m²	
	100% recycled PP	21	6,7 kJ/m²	
(Matei et al., 2017)	Recycled PP	2	4,4 kJ/m²	Additives (e.g., SIS30) significantly improve strength and impact properties.
	Recycled PP + 5% PE + 10% SEBS	7	8,6 kJ/m²	
	Recycled PP + 5% PE + 10% SEBS + 1% Topanol (SIS30)	12	21,8 kJ/m²	
(Barbosa et al., 2020)	100% Virgin PP	32	3,6 J	High recycled content reduces tensile strength and impact resistance.
	30% Virgin PP + 70% Recycled PP	11	0,14 J	
(Gabriel & Ananditto, 2020)	100 % virgin PP	28	-	A 70/30 virgin-to-recycled PP blend retained good tensile strength and rigidity up to 8 recycling cycles.
	70% Virgin PP + 30% Recycled PP (6th cycle)	30		
	100% recycled PP (6th cycle)	25		
(Poveda & A e Silva, 2019)	100% Post-Consumer Recycled PP	30	-	Additives lower mechanical properties. Recycled PP retains relatively high tensile strength.
	90% PCR PP + 10% Elastomer	27		
	99.08% PCR PP + 0.02% Organic Peroxide	29		

(Domingues et al., 2020)	96.4% Post-Consumer Recycled PP (Nescafé® capsules)	30	102 J/m³	Excellent properties are obtained from a clean post-consumer stream.
	100% Post-Consumer Recycled PP (plastic filter)	34	118 J/m³	
(Kozderka et al., 2017)	Virgin High Impact PP	58	-	Strength progressively decreases with additional recycling cycles.
	Recycled High Impact PP (6 cycles)	30		
	Recycled High Impact PP (12 cycles)	19		

**Note: Values are reported as provided by the original authors. Most studies express impact resistance as energy absorbed per unit area (kJ/m²) or per unit volume (J/m³). However, at least one study reports the total absorbed energy in absolute units (J), without normalizing by specimen dimensions*
Source: Self-elaboration.

3.2 Main Methodological Approaches

To evaluate recycled PP, researchers apply a range of mechanical and thermal testing techniques.

The most common mechanical tests include:

- *Tensile test* to assess structural performance (all articles reviewed).
- *Impact resistance test* (Izod or Charpy) to evaluate ductility and toughness (Arese *et al.*, 2025; Barbosa *et al*., 2017, 2020; Domingues et al., 2020; Matei *et al.*, 2017)prompting the automotive industry to transition towards greener solutions. This includes producing lighter vehicles with sustainable materials, like recycled plastics. Understanding the behavior of these new recycled compounds is crucial, especially regarding their response to ageing and stress conditions throughout a vehicle's lifecycle. This study aims to investigate the mechanical property variations of virgin and recycled talc-filled polypropylene (PP.
- In some cases, *flexural test* is also applied (Arese *et al*., 2025).

In the reviewed studies, tensile properties were typically evaluated using standardized procedures such as ISO 527 and ASTM D638-02a, while impact resistance was assessed following ISO 180/A, ISO 179, or ASTM D256-02, depending on the test configuration and specimen type. However, not all articles explicitly reported the testing standard or sample geometry, which limits direct comparability. The lack of consistency in methodological reporting is a recurring issue in literature and highlights the need for more transparent and harmonized testing protocols.

For thermal and structural analysis, the following techniques are commonly used:

- *Differential Scanning Calorimetry (DSC)* to measure melting temperature (Tm), crystallization temperature (Tc), and infer the level of crystallinity (Arese et al., 2025; Domingues *et al*., 2020; Matei et al., 2017).

- *Thermogravimetric Analysis (TGA)* to study thermal stability and decomposition temperatures (Arese *et al.*, 2025; Domingues *et al*., 2020).

- *Fourier-Transform Infrared Spectroscopy (FTIR)* to identify potential chemical changes or oxidation products (Arese *et al*., 2025; Gabriel & Ananditto, 2020; Matei *et al*., 2017).

- *Melt Flow Index (MFI)* tests to estimate the fluidity of the polymer melt and track molecular weight changes across recycling cycles (Barbosa et al., 2020; Matei *et al*., 2017; Poveda & A e Silva, 2019)

- *X-Ray Diffraction (XRD)* to assess changes in crystalline structure, degree of crystallinity, and detect structural defects after recycling (Domingues et al., 2020; Matei *et al*., 2017).

These methods provide a comprehensive view of how recycling affects the mechanical properties, thermal transitions, and processability of PP, allowing researchers to correlate material behavior with structural performance.

3.3 Critical Analysis

This literature review revealed both converging findings and significant inconsistencies across studies related to recycled polypropylene (PP). While there is broad agreement that tensile strength is generally well preserved, the magnitude of property loss varies significantly, and some data sets appear contradictory. For example, one study (Barbosa *et al*., 2017) showed a minimal decrease in tensile strength (~4%), while another (Barbosa et al., 2020) reported a drop from 32 MPa to 21.3 MPa (≈33%) under similar recycling conditions. These differences may stem from variations in feedstock quality, additive use, or testing conditions, yet in many cases, these parameters are not clearly documented.

Another recurring issue is the limited transparency regarding the origin and history of recycled PP samples. Only a few papers specify whether the recycled content comes from industrial waste (Arese *et al*., 2025), post-consumer items (Domingues et al., 2020; Matei *et al*., 2017), or specific product streams (Poveda & A e Silva, 2019). This lack of detail makes it difficult to generalize findings or replicate experiments. In real-world scenarios—especially in low-income contexts—recycled PP often comes from mixed or contaminated sources, and this reality is underrepresented in the literature.

Additionally, many studies present mechanical results without corresponding structural or chemical data, making it difficult to establish clear causal links between molecular degradation and performance loss (Barbosa *et al*., 2017, 2020; Kozderka *et al*., 2017; Poveda & A e Silva, 2019) Only a few works integrate tensile and impact tests, with FTIR or XRD data comprehensively (Arese *et al*., 2025; Domingues et al., 2020; Matei et al., 2017).

From a methodological standpoint, there is a noticeable absence of uniform standards for processing and testing. Some articles use ISO 527 or ASTM D638-02a tensile bars, others report “dog-bone” samples of undefined geometry, and several fail to report sample dimensions entirely. The same inconsistency appears with processing temperatures, recycling cycle conditions, and cooling rates—all factors that dramatically affect crystallinity and mechanical properties. Establishing clearer standards for evaluating recycled PP would enable more accurate cross-study comparisons and facilitate material certification for industrial applications.

Moreover, few studies adopt a life-cycle or application-based perspective (Kozderka et al., 2017). The majority focus on basic material characterization but rarely assess how recycled PP would behave in real-world applications such as packaging, furniture, or automotive parts. Future studies would benefit from bridging the gap between laboratory results and industrial applicability.

Another key challenge identified is the limited exploration of long-term aging and multi-cycle reprocessing behavior. Only a handful of studies (Arese *et al*., 2025; Gabriel & Ananditto, 2020; Kozderka *et al.*, 2017) have evaluated the cumulative effects of repeated thermal and mechanical processing, which are critical for understanding material durability in secondary applications. Additional research on multi-cycle degradation behavior would allow the definition of reliable thresholds for reuse and structural decay.

3.4 Future Perspectives

Despite these limitations, promising strategies have emerged to enhance the performance of recycled PP. One of the most effective approaches is the use of tailored additive systems to compensate for specific property losses. Fillers like talc have proven effective in increasing rigidity and thermal stability, particularly in applications where strength is prioritized (Arese *et al*., 2025; Matei *et al*., 2017). Meanwhile, elastomeric modifiers have shown potential for improving impact resistance, making recycled PP suitable for components subjected to dynamic loads (Matei *et al*., 2017). Some studies suggest that combining mineral fillers with elastomers may offer synergistic benefits—enhancing both strength and toughness—when properly balanced (Arese *et al.*, 2025; Matei *et al.*, 2017), although optimization remains a challenge in terms of cost, process complexity, and future recyclability.

The development of closed-loop recycling systems represents another promising direction. When recycled PP is reused within the same product family (e.g., automotive parts recycled into new automotive parts), quality control is easier, and additive systems can be more precisely tailored. For instance, as discussed by (Sambyal *et al.*, 2025) several major automakers have implemented programs to recycle post-industrial PP waste into new automotive components, supporting the transition toward a more circular economy in polymer manufacturing.

Incorporating dynamic mechanical analysis (DMA) could provide deeper insights into the viscoelastic behavior of recycled PP under dynamic loading conditions, offering a more comprehensive understanding of its long-term performance (Menard & Menard, 2020).

Finally, advances in sorting and preprocessing technologies—such as near-infrared (NIR) sorting, filtration, and compatibilization—could significantly improve feedstock purity and reduce material variability. These improvements, combined with smart additive strategies and standardized testing protocols, could allow recycled PP to approach the performance levels of virgin material in a broader range of applications.

4. CONCLUSION

This review set out to examine how mechanical recycling affects the mechanical performance of polypropylene (PP), and under what conditions recycled PP can be considered a viable substitute for virgin material. The evidence analyzed suggests that tensile strength and structural rigidity are generally retained, particularly when suitable additive systems are applied. However, recurring challenges remain, especially regarding impact resistance.

From a technical standpoint, the findings show that the performance of recycled PP is not inherently compromised but rather depends on several critical factors: the quality and origin of the feedstock, the specific reprocessing conditions, and the presence or absence of property-enhancing additives. Broad generalizations about recycled PP are therefore inadequate unless supported by detailed characterization data.

It can be concluded that recycled PP can be a functional and sustainable material solution, particularly in non-structural or low-impact applications, and when combined with fillers or elastomeric modifiers tailored to the end-use context. Nevertheless, to ensure broader acceptance and reliability, further research is required, especially studies focusing on multi-cycle processing, real-world applications, and the establishment of standardized testing and reporting protocols.

Ultimately, the successful integration of recycled PP into industrial production chains will depend not only on technological improvements but also on transparency, reproducibility, and application-oriented research strategies that align with the principles of a circular economy.

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