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State of the art of thermal molding technologies applied to plastic recycling: A systematic review

Estado del arte de las tecnologías de moldeo térmico para reciclaje de plásticos: una revisión sistemática


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State of the art of thermal molding technologies applied to plastic recycling: A Systematic Review

Estado del arte de las tecnologías de moldeo térmico para reciclaje de plásticos: una revisión sistemática

Abstract

The increasing generation of plastic waste and the limited efficiency of recycling systems demand technologies capable of transforming recovered materials with stability and performance. The objective of this systematic review was to synthesize recent advances in thermal molding technologies applied to plastic recycling. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The search was carried out in the Scopus and Web of Science databases on May 27, 2025, applying filters for accessibility, language, document type, and the 2014–2024 period. After screening and the application of inclusion and exclusion criteria, 26 articles were selected for qualitative analysis. The results indicate that injection molding is the most widely used technology for processing recycled polymers, followed by compression molding and, less frequently, rotational molding, thermoforming, and cast film processes. Recycled polyolefins (polypropylene and polyethylene) predominate as raw materials, whereas polyethylene terephthalate, polystyrene, and acrylonitrile butadiene styrene show lower usage frequency. The evidence indicates that process parameters, compatibilization, reinforcement, and thermal history have a decisive influence on molding efficiency and the performance of recycled materials. In addition, advances were identified in equipment development and in the integration of pre-conditioning stages. Overall, the findings suggest that an integrated approach combining thermal control, formulation, and process design is essential to improve the stability and quality of products manufactured from recycled polymers.

Keywords: plastic recycling, molding technologies, polymers, mechanical properties, mechanical recycling

Resumen

La creciente generación de residuos plásticos y limitada eficiencia de los sistemas de reciclaje exigen tecnologías capaces de transformar materiales recuperados con estabilidad y desempeño. El objetivo de esta revisión sistemática fue sintetizar los avances recientes en tecnologías de moldeo térmico aplicadas al reciclaje de plásticos. Se desarrolló conforme a las directrices *Preferred Reporting Items for Systematic reviews and Meta-Analyses* (PRISMA) 2020. La búsqueda se realizó en las bases de datos *Scopus* y *Web of Science* el 27 de mayo de 2025, aplicando filtros de accesibilidad, idioma, tipo de documento y el periodo 2014–2024. Tras el cribado y la aplicación de criterios de inclusión-exclusión, se seleccionaron 26 artículos para el análisis cualitativo. Los resultados indican que el moldeo por inyección constituye la tecnología más empleada para procesar polímeros reciclados, seguido del moldeo por compresión y, con menor frecuencia, rotomoldeo, termoformado y los procesos de película fundida. Las poliolefinas recicladas (Polipropileno y Polietileno) predominan como materias primas, mientras que Tereftalato de Polietileno, Poliestireno y Acrilonitrilo Butadieno Estireno presentaron menor frecuencia de uso. La evidencia indica que los parámetros de proceso, la compatibilización, el refuerzo y el historial térmico influyen de manera determinante en la eficiencia del moldeo y en el desempeño del material reciclado. Adicionalmente, se identificaron avances en el desarrollo de equipos y en la integración de etapas de acondicionamiento previo. En conjunto, los hallazgos sugieren que un enfoque integrado de control térmico, formulación y diseño del proceso es esencial para mejorar la estabilidad y la calidad de los productos fabricados a partir de polímeros reciclados.

Palabras clave: reciclaje de plásticos, tecnologías de moldeo, polímeros, propiedades mecánicas, reciclaje mecánico

Córdova Palma, J. L., López Ramos, A., Sosa Olivier, J. A., & Laines Canepa, J. R. (2026). State-of-the-Art of the Thermal Molding Technologies for Plastic Recycling: a systematic review. *Transdigital*, *7*(13). e571. https://doi.org/10.56162/transdigital571

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1. INTRODUCTION

Global plastic production exceeds 400 million tonnes per year, and less than 10% is effectively recycled; the remainder is disposed of in landfills or ends up dispersed in terrestrial and marine ecosystems (United Nations Environment Programme [UNEP], 2023; Organisation for Economic Co-operation and Development [OECD], 2022). The plastic life cycle, which includes raw material extraction, polymerization, manufacturing, transportation, use, and final disposal, generated approximately 1.8 metric tonnes of greenhouse gas emissions in 2019, representing 3.4% of global emissions (UNEP, 2023). This scenario highlights the need to strengthen recycling strategies in order to reduce the demand for virgin materials and the emissions associated with their production. In Mexico, approximately 5.7 million tonnes of mismanaged plastic waste are generated annually, underscoring the need to implement more efficient valorization technologies (World Wildlife Fund [WWF], 2024).

Among the available routes, mechanical recycling constitutes the predominant and most versatile alternative, accounting for more than 90% of plastic recycled globally (Chen & Hu, 2024). This process enables the reprocessing of polymers without altering their chemical structure through operations such as sorting, washing, shredding, and extrusion (Li et al., 2022). Thermoplastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) account for nearly 80% of total plastic consumption, which explains their predominance in mechanical recycling due to their ability to be melted and reprocessed multiple times (Sultana et al., 2022). Once regranulated or converted into flakes, these materials require conversion techniques for transformation into final products; injection molding and extrusion stand out as the most widely used processes for both virgin and recycled polymers (Ragaert et al., 2017).

Conventional thermal molding technologies constitute the most well-established industrial processes for the manufacturing of plastic products (Polychronopoulos & Vlachopoulos, 2018). These technologies operate through polymer melting, with controlled flow into a mold or die followed by solidification, providing production efficiency, repeatability, and scalability. Injection molding accounts for approximately 43% of global plastic processing (Kalauni et al., 2025) and is essential for the production of packaging, automotive components, and engineering parts, among other applications (Fu et al., 2020; Czepiel et al., 2023). However, recycled polymers exhibit variations in molecular weight, crystallinity, and thermal stability, which require specific adjustments to molding parameters in order to achieve properties comparable to those of virgin materials.

Although these technologies are widely implemented at the industrial level, scientific evidence regarding their application to recycled polymers remains fragmented and heterogeneous, limiting the identification of trends, methodological approaches, and systematic technological contributions. In this context, the present systematic review, developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, aimed to synthesize recent evidence on conventional thermal molding technologies

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applied to the recycling of synthetic plastics, describing research lines, experimental methods, and technological contributions. The scope was limited to conventional thermal molding, excluding additive manufacturing.

2. METHOD OF RESEARCH

The present systematic review was structured based on a protocol previously defined by the authors, which included the research question, search strategy, selection criteria, and the processes for data extraction and synthesis. Given the engineering-focused scope of the study, the protocol was not registered in public platforms.

This research was conducted under the framework of a systematic literature review, aimed at identifying and analyzing recent advances in thermal molding technologies applied to the mechanical recycling of plastics, evaluating their influence on process efficiency and the quality of the molded product. The review was carried out in accordance with the PRISMA 2020 statement guidelines, with the purpose of ensuring transparency, comprehensiveness, and reproducibility of the methodological procedure (Page et al., 2021).

The research question guiding this review was: What advances and trends are reported in the recent literature regarding the use of conventional thermal molding technologies applied to plastic recycling? To address this question, a systematic search protocol was established and conducted on May 27, 2025, using the Web of Science and Scopus databases, selected for their coverage and specialization in materials engineering and polymer science.

Based on the criteria defined by the research question, a Boolean semantic search equation was formulated combining terms related to thermal molding technologies, plastic recycling, and performance indicators. The general equation used was as follows:

> *(casting technolog* OR molding technolog* OR casting method* OR mold technolog* OR casting process*) AND (plastic recycl* OR polymer recycl* OR plastic waste OR waste plastic* OR plastic reuse) AND (advancement* OR innovation* OR improvement* OR development* OR performance OR efficiency OR process improvement*)**

Given that each database presents syntactic differences, the equation was adapted to the specifications of each platform:

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Web of Science (Original version):

(casting technolog OR molding technolog OR casting method* OR mold technolog* OR casting process*) AND (plastic recycl* OR polymer recycl* OR plastic waste OR waste plastic* OR plastic reuse) AND (advancement* OR innovation* OR improvement* OR development* OR performance OR efficiency OR process improvement*).*

Scopus (modified version):

("casting technology" OR "molding technology" OR "casting method" OR "mold technology" OR "casting process") AND ("plastic recycling" OR "polymer recycling" OR "plastic waste" OR "waste plastics" OR "plastic reuse") AND (advancements OR innovations OR improvements OR development OR performance OR efficiency OR "process improvement").

To refine the results and ensure thematic relevance, the general filters shown in Table 1 were applied.

Table 1
Filters applied during the systematic search

Criteria	Description
Time span	2014 – 2024
Document type	Scientific articles
Language	English
Open Access	Yes

Additionally, in the Scopus database, thematic sub-area filters were applied to improve the relevance of the results. The selected sub-areas were: *plastic recycling, mechanical properties, polymer, compression strength, reinforced plastic, polymer blends, plastic products, polypropylene, thermodynamic stability, injection molding, plastic waste, solution-casting method, polyethylene terephthalates, casting method, extrusion, flexural strength, polystyrene, polyethylenes, and casting.*

The study selection process was carried out in accordance with the identification, screening, and inclusion phases established in the PRISMA 2020 statement. During the screening phase, the retrieved records were organized and refined using the Mendeley reference management software, which was used to remove duplicates.

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Subsequently, titles and abstracts were reviewed to exclude studies with approaches different from that of the review, as well as articles that, despite addressing the general topic, were not accessible in full text.

The remaining documents were analyzed in full text by systematically applying the inclusion and exclusion criteria described in Table 2. Studies that met all the established criteria constituted the final set of works selected in the inclusion phase and were considered for qualitative analysis. The complete process flow is presented in the PRISMA flow diagram (Figure 1), which summarizes the records identified, screened, excluded, and ultimately included in the review.

Table 2
Inclusion and exclusion criteria applied in the systematic review

Criteria	Inclusion (I)	Exclusion (E)
1. Type of process	Focus on conventional thermal molding technologies applied to recycling: studies that analyze, optimize, or evaluate conventional thermal molding processes for plastics, such as injection molding, compression molding, extrusion, rotational molding, or film casting.	Processes outside conventional thermal molding: studies focused on non-thermal valorization routes or manufacturing processes other than molding, such as chemical recycling, biodegradation, or additive manufacturing.
2. Type of material	Use of post-consumer or post-industrial synthetic plastics as feedstock: studies that employ recycled synthetic plastics, used wholly or partially as raw material in molding processes, with or without additives or reinforcements.	Use of virgin or non-recycled plastics: studies that utilize first-generation plastics or materials without verifiable recycled content.
3. Type of evidence	Experimental results on process efficiency or product quality: studies that present empirical data on mechanical, thermal, rheological properties, or indicators of process efficiency.	Lack of experimental results: theoretical studies, narrative reviews, or simulations without verifiable experimental data.
4. Research focus	Technological or process-improvement focus in molding: studies that provide technical innovations, parameter optimization, or strategies that enhance process efficiency or the quality of the molded product.	Lack of a technological or process-improvement focus: studies that apply molding processes without contributing optimization, innovation, or analysis aimed at improving the process or the performance of the recycled material.

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3. Results

3.1. Study Selection

The study selection process was conducted in accordance with the PRISMA 2020 guidelines. Initially, 1,868 records were identified: 1,089 from Web of Science and 779 from Scopus. Subsequently, the filters established in Table 1 were applied, which allowed 1,443 records from the initial search to be excluded.

The remaining records were exported to the Mendeley reference management software, where 11 duplicates were identified and removed. Following this refinement, 414 studies advanced to the screening phase.

During the screening phase, 339 records were excluded through the reading of titles and abstracts because they did not align with the thematic focus of the review. Additionally, 6 articles were excluded due to lack of access or readability of the full text, resulting in 69 studies for full-text evaluation.

At this stage, the inclusion and exclusion criteria specified in Table 2 were systematically applied. As a result, 15 articles were excluded for not corresponding to conventional thermal molding technologies, 26 for not employing the specified type of material (post-consumer or post-industrial recycled synthetic plastics), and 2 for not providing elements of innovation or improvement in the molding process. Finally, 26 articles met all the criteria and were integrated into the inclusion phase, forming the final basis for qualitative analysis.

Figure 1 summarizes the complete flow of the selection process, representing the number of records identified, refined, excluded, and ultimately included in the review.

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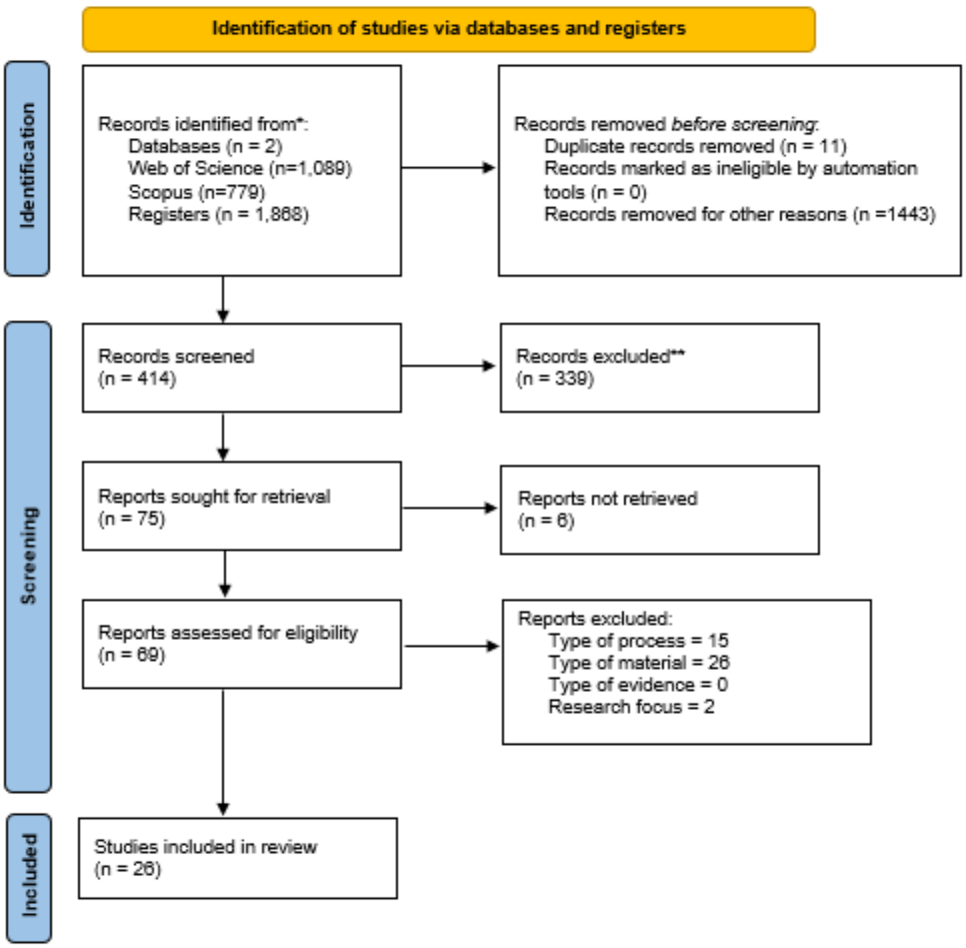
Figure 1

PRISMA 2020 flow diagram



3.2. Characterization and Description of the Included Studies

The 26 included studies cover the period from 2017 to 2024, with a sustained increase in publication volume since 2020.

Figure 2 shows the temporal distribution of the included studies, revealing a significant concentration of publications between 2020 and 2024, representing more than 80% of the total analyzed publications.

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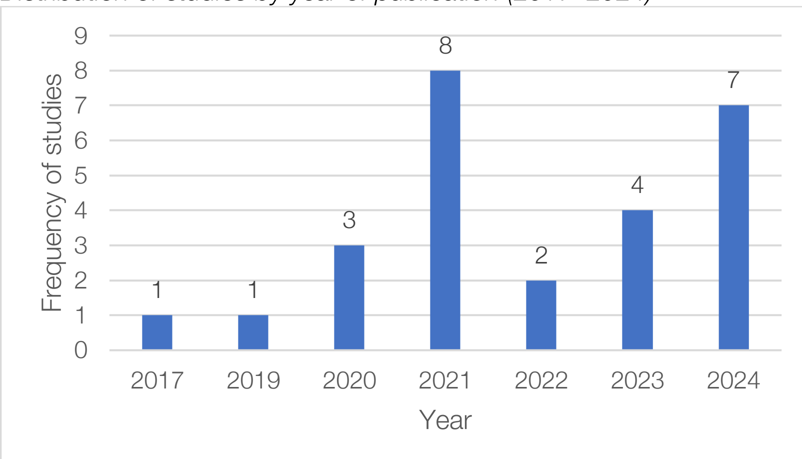
Figure 2

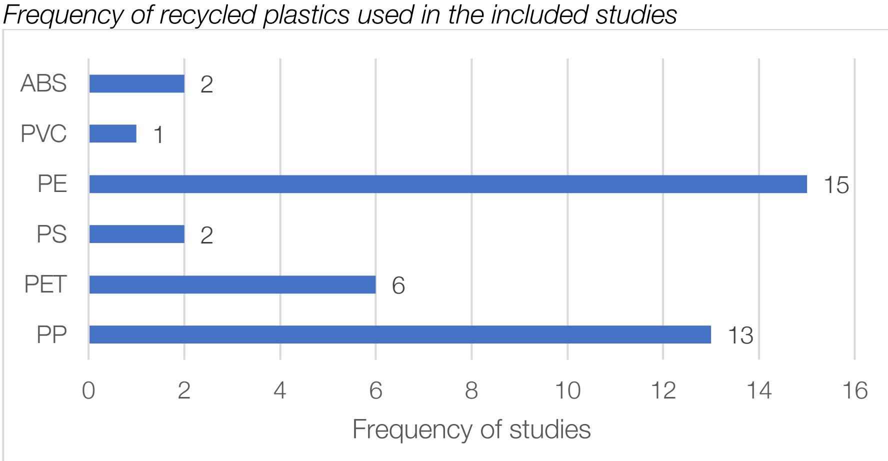
Distribution of studies by year of publication (2017–2024)



Regarding the materials employed, recycled polymers derived from post-consumer and post-industrial waste predominated. Figure 3 shows the frequency of use of each identified polymer type. Recycled polyolefins (PE and PP) were the most frequently used materials, followed by PET, PS, ABS, and PVC, with proportionally lower representation across the overall set of studies.

Figure 3

Frequency of recycled plastics used in the included studies



The evaluated studies employed various final molding technologies for the transformation of recycled polymers. Figure 4 presents the frequency of use of each of these technologies. Injection molding was the most

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widely used technique, reported in 15 studies, followed by compression molding/pressing, identified in 9 studies. Technologies such as rotomolding, thermoforming, and cast and blown film processes were reported less frequently.

Figure 4

Conventional thermal molding technologies employed in the included studies

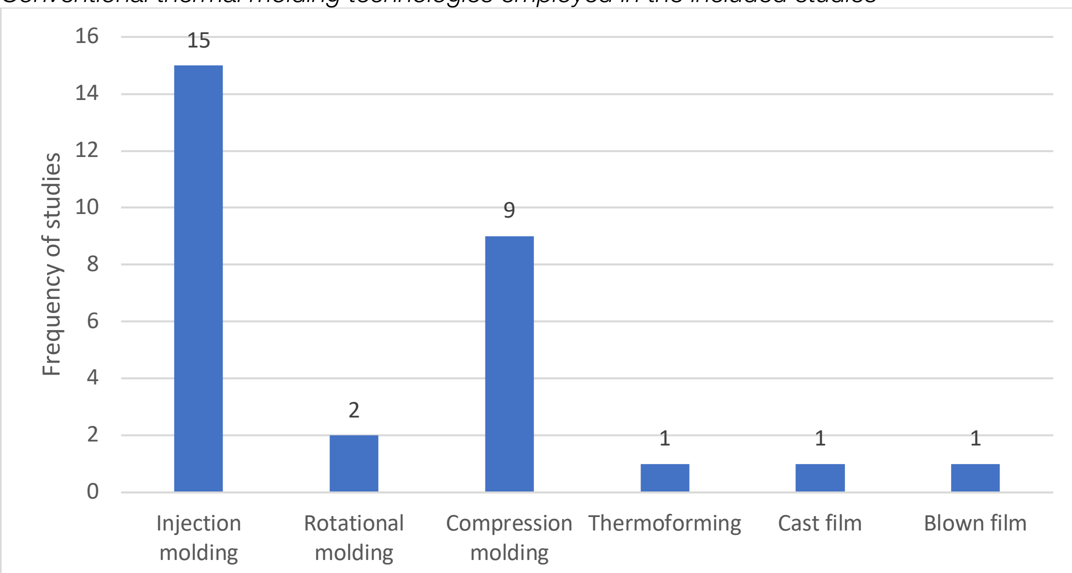

Table 3 summarizes the combinations identified between final molding technologies and the recycled polymers used in the studies.

Table 3

End-use molding technologies applied to each recycled polymer type.

Molding technology	PP	PE	PET	PS	PVC	ABS
Compression molding / pressing	5	7	2	1	–	–
Injection molding	7	7	5	1	1	2

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Table 3

End-use molding technologies applied to each recycled polymer type.

Molding technology	PP	PE	PET	PS	PVC	ABS
Rotational molding	1	2	–	–	–	–
Thermoforming	–	–	1	–	–	–
Cast film	1	1	–	–	–	–
Blown film	1	1	–	–	–	–

In 13 studies, extrusion was used as a prior conditioning process. In seven of these studies, its application was specified for the preparation of blends prior to final molding. Figure 5 shows the frequency with which extrusion was integrated in combination with each final molding technology.

Figure 5

Frequency of studies applying extrusion prior to molding technologies

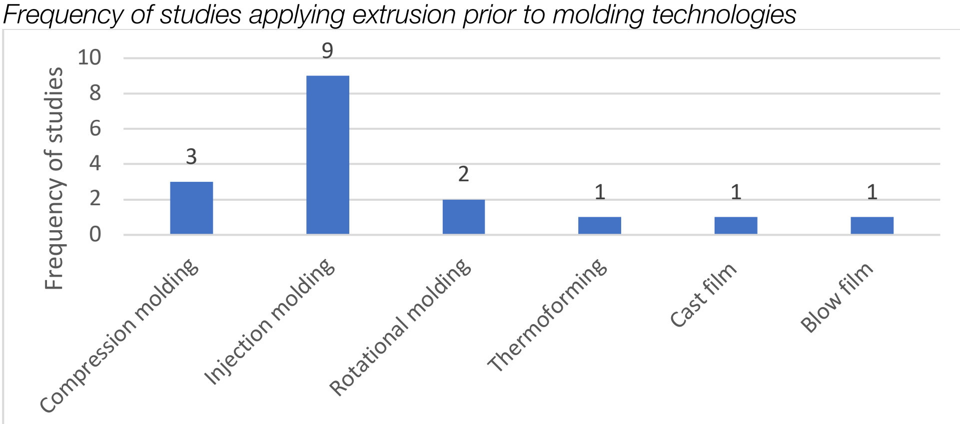

Table 4 provides a detailed synthesis of the articles included in the review, specifying the author and year of publication, title, digital object identifier (DOI), type of recycled plastic, and the molding technology employed.

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Table 4

Studies included in the systematic review

N°	Author, year	Title	DOI	Recycled plastic	Molding technology
1	Takenaka, 2017	*Creation of Advanced Recycle Process to Waste Container and Packaging Plastic – Polypropylene Sorted Recycle Plastic Case –*	10.1678/rheology.45.139	PP (traces of PE)	Hot pressing
2	Tominaga et al. (2019)	*Advanced recycling process for waste plastics based on physical degradation theory and its stability*	10.1007/s10163-018-0777-7	PP	Hot pressing
3	De Castro et al., 2020	*Recycled Green PE Composites Reinforced with Woven and Randomly Arranged Sisal Fibres Processed by Hot Compression Moulding*	10.2478/ata-2020-0013	HDPE and green HDPE (produced from sugarcane ethanol)	Hot compression molding
4	Ju et al. (2020)	*Mechanical Properties of Coal Ash Particle-Reinforced Recycled Plastic-Based Composites for Sustainable Railway Sleepers*	10.3390/polym12102287	MPW composites (PP, LDPE, and HDPE) + HDPE	Compression molding
5	Synyuk et al. (2020)	*Development of Equipment for Injection Molding of Polymer Products Filled with Recycled Polymer Waste*	10.3390/polym12112725	PVC	Injection molding
6	Bocz et al. (2021)	*Application of low-grade recyclate to enhance reactive toughening of poly(ethylene terephthalate)*	10.1016/j.polymdegradstab.2021.109505	PET	Injection molding
7	Cestari et al. (2021)	*Use of virgin/recycled polyethylene blends in rotational moulding*	10.1515/polyeng-2021-0065	HDPE	Rotational molding and compression molding

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Table 4

Studies included in the systematic review

N°	Author, year	Title	DOI	Recycled plastic	Molding technology
8	Czarnecka et al. (2021)	*Polyethylene/Polyamide Blends Made of Waste with Compatibilizer: Processing, Morphology, Rheological and Thermo-Mechanical Behavior*	10.3390/polym13142385	PE (LDPE)/PA6 blend	Injection molding
9	Garcia et al. (2021)	*Comparative LCA of conventional manufacturing vs. additive manufacturing: the case of injection moulding for recycled polymers*	10.1080/19397038.2021.1990435	ABS	Injection molding vs. additive manufacturing (FDM, 3D printing)
10	Gupta et al. (2021)	*Novel sustainable materials from waste plastics: compatibilized blend from discarded bale wrap and plastic bottles*	10.1039/d1ra00254f	PET/LLDPE blend	Injection molding
11	Huang & Peng (2021)	*Number of Times Recycled and Its Effect on the Recyclability, Fluidity and Tensile Properties of Polypropylene Injection Molded Parts*	10.3390/su131911085	PP	Injection molding
12	Möllnitz et al. (2021)	*Processability of Different Polymer Fractions Recovered from Mixed Wastes and Determination of Material Properties for Recycling*	10.3390/polym13030457	Plastic fractions recovered from mixed municipal/commercial waste (SRF): PE, PP, PS, PET	Vacuum compression molding
13	Ronkay et al. (2021)	*Plastic waste from marine environment: Demonstration of possible routes for recycling by different manufacturing technologies*	10.1016/j.wasman.2020.09.029	PET	Injection molding ,3D printing and thermoforming
14	Bashirgonbadi et al. (2022)	*Quality evaluation and economic assessment of an improved*	10.1016/j.wasman.2	Post-consumer flexible	Injection molding and Film blowing, cast film extrusion

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Table 4

Studies included in the systematic review

N°	Author, year	Title	DOI	Recycled plastic	Molding technology
		mechanical recycling process for post-consumer flexible plastics	022.08.018	plastics (PCFP): Nearly pure PE; PE/rPP/non-PO blends; PE/PP blends with different proportions.	
15	Pick et al. (2022)	*Assessment of processibility and properties of raw post-consumer waste polyethylene in the rotational moulding process*	10.1515/polyeng-2021-0212	PE/PP blend with pigments and contaminants	Rotational molding
16	Belblidia et al. (2023)	*Recycling high impact polystyrene: Material properties and reprocessing in a circular economy business model*	10.1177/14777606231168653	HIPS (high-impact polystyrene)	Injection molding
17	Daniele et al. (2023)	*From Nautical Waste to Additive Manufacturing: Sustainable Recycling of High-Density Polyethylene for 3D Printing Applications*	10.3390/jcs7080320	HDPE	Compression molding and 3D printing
18	Ji & Jung (2023)	*Effect of the multiple injection process on the structural and mechanical properties of PP impact copolymers focusing on the deformation of ethylene-propylene copolymer*	10.1016/j.polymertesting.2023.108051	Polypropylene impact copolymers (PP/EPC)	Multiple injection molding
19	Sanetuntikul et al. (2023)	*A circular economy use of waste metalized plastic film as a reinforcing filler in recycled polypropylene packaging for injection molding applications*	10.1016/j.clet.2023.100683	PP blend with MF (LLDPE/PET/Al multilayer)	Injection molding

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Table 4
Studies included in the systematic review

N°	Author, year	Title	DOI	Recycled plastic	Molding technology
20	Dziadowiec et al. (2024)	*Development of Technologies for Processing Polypropylene Foil Waste and Their Use in the Production of Finished Products*	10.3390/ma17215192	Metallized multilayer waste (PP, BOPP, or BOPET + Al) blended with virgin PP	Injection molding
21	Karahan et al. (2024)	*Comparative study of virgin and recycled polyethylene terephthalate and polypropylene intermingled thermoplastic composites*	10.1002/pc.29209	PET	Hot compression molding
22	Müller et al. (2024)	*Mechanical and Thermal Degradation-Related Performance of Recycled LDPE from Post-Consumer Waste*	10.3390/polym16202863	LDPE	Injection molding
23	O'Rourke et al. (2024)	*Diverted from landfill: Manufacture and characterisation of composites from waste plastic packaging and waste glass fibres*	10.1016/j.susmat.2024.e00851	Packaging plastic blends (waste mixed plastics, wMP: PE/PP)	Compression molding
24	Sinchai et al. (2024)	*Development of a Low-Cost Automated Injection Molding Device for Sustainable Plastic Recycling and Circular Economy Applications*	10.3390/inventions9060124	HDPE	Injection molding
25	Singkronart et al. (2024)	*Immiscible Polymer Blends Made from Industrial Shredder Residue Mixed Plastic with and without Melt Blending*	10.1021/acsapm.4c00360	Industrial plastic waste blend (ABS, PP, PE)	Injection molding

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Table 4

Studies included in the systematic review

N°	Author, year	Title	DOI	Recycled plastic	Molding technology
26	Stachowiak et al. (2024)	*Analysis of Mechanical and Thermal Properties of Polymer Materials Derived from Recycled Overprinted Metallized PP Films*	10.3390/ma17081739	PP	Injection molding

3.3. Classification of Studies and Qualitative Synthesis of Results

The 26 included studies were classified into five categories according to their predominant focus, with the aim of synthesizing recurring themes in the literature. The assignment considered the objectives, methodology, and predominant content of each article, with each study recorded exclusively in the dominant category to maintain analytical consistency.

The identified categories were evaluation of molding parameters, formulation of recycled blends, comparison of molding technologies, process modification and equipment design, and evaluation of recyclability or material degradation. Table 5 presents the distribution of studies within each category.

Table 5

Approaches observed in the included studies

Code	Category	Main focus	Included studies (author, year)
A	Evaluation of molding parameters	Effect of molding parameters (temperature, pressure, cycle times, and other operational variables) on recycled material quality and process performance.	Takenaka et al. (2017); Tominaga et al. (2019); Möllnitz et al. (2021); Pick et al. (2022)
B	Formulation and blending of recycled materials	Material innovation: development of blends, compatibilization strategies, or use of additives to improve properties.	De Castro et al. (2020); Ju et al. (2020); Bocz et al. (2021); Cestari et al. (2021); Czarnecka et al. (2021); Gupta et al. (2021); Daniele et al. (2023); Sanetuntikul et al. (2023); Dziadowiec et al. (2024); Karahan et al. (2024); O’Rourke et al. (2024)
C	Comparison of molding technologies	Technical and/or energy evaluation of different molding technologies applied to recycled plastics	Garcia et al. (2021)

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Table 5

Approaches observed in the included studies

Code	Category	Main focus	Included studies (author, year)
D	Modification of the process or equipment	Methodological and engineering innovations applied to molding processes	Synyuk et al. (2020); Bashirgonbadi et al. (2022); Sinchai et al. (2024); Singkronart et al. (2024)
E	Assessment of recyclability or material degradation	Material behavior in terms of recyclability, reprocessability, and thermal or mechanical degradation	Huang & Peng (2021); Ronkay et al. (2021); Belblidia et al. (2023); Ji & Jung (2023); Müller et al. (2024); Stachowiak et al. (2024)

3.4. Types of Tests and Experimental Procedures

The included studies reported a variety of experimental tests to evaluate molding processes and the resulting properties of the obtained recycled materials. The tests were grouped into five categories according to their nature and purpose: mechanical, thermal, rheological, structural/morphological/compositional, and material stability or behavior. Table 6 presents these categories and the frequency of studies in which they were reported.

Table 6

Experimental test types reported in the included studies

Test category	Examples of tests	Frequency of studies
Mechanical	Tensile, impact, flexural, compression, fatigue tests	25
Thermal	DSC, TGA, DMA, HDT, OIT, Vicat, CLTE	20
Rheological	MFI/MFR, rotational or oscillatory rheometry, torque rheometer	14
Structural, morphological, and compositional characterization	SEM, FTIR, XRD, EDS, AFM, μCT	19
Material stability and behavior	Water absorption, UV/thermal aging, colorimetry, flammability	8

In addition to the general classification shown in Table 6, the most frequently used tests were quantified, and their frequency is presented in Figure 6.

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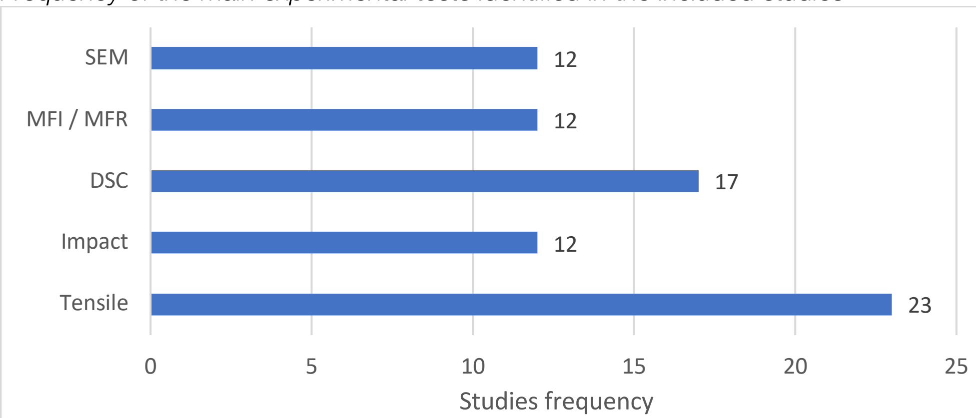
Figure 6

Frequency of the main experimental tests identified in the included studies



The most frequently used tests were tensile testing and differential scanning calorimetry (DSC), followed by impact testing, scanning electron microscopy (SEM), and melt flow index/melt flow rate (MFI/MFR) measurements.

4. Discussion

The analyzed studies confirm that conventional thermal molding technologies continue to be among the most well-established routes for transforming recycled polymers through mechanical recycling. This finding is consistent with the literature, which recognizes mechanical recycling as the predominant pathway for the valorization of plastic waste (>90% of global recycling) (Chen & Hu, 2024; Sultana et al., 2022). Likewise, polyolefins and PET, which constitute the majority of post-consumer waste in the packaging sector (Beghetto et al., 2021), are also the polymers most frequently employed in the included studies, reflecting their wide availability and dominant participation in global plastic demand (Li et al., 2022). Among the evaluated technologies, injection molding maintains a dominant role due to its ability to produce parts with complex geometries, high precision, and short cycle times (Czepiel et al., 2023; Fu et al., 2020), which explains its prevalence among the reported processes.

In the category focused on molding parameters, the evaluated studies demonstrate that the optimization of temperature, pressure, residence time, and cooling conditions has a decisive influence on the performance of recycled polymers. In recycled polypropylene, elevated temperatures followed by rapid cooling (quenching) significantly improve mechanical strength, reaching values comparable to those of virgin material processed under

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standard conditions (Takenaka et al., 2017; Tominaga et al., 2019). Both studies also observed that stabilization of these properties requires optimized annealing to avoid variations associated with crystallinity.

In the category of formulation and recycled blends, the studies agree that compatibilization and reinforcement constitute effective strategies to improve properties affected by thermal history or compositional heterogeneity. For example, blends of recycled PP with metallized or lignocellulosic waste exhibited reductions in strength and modulus due to phase incompatibility, a phenomenon widely documented for PP–PE systems without compatibilization (Sanetuntikul et al., 2023). The incorporation of MAPP or elastomers (such as POE-GMA) resulted in more homogeneous blends and significant increases in impact strength, even up to four times compared with unmodified samples (Dziadowiec et al., 2024).

Mineral and fibrous reinforcements also generate substantial improvements: the use of glass fibers markedly increased modulus and strength (O'Rourke et al., 2024), while the addition of coal ash enabled the development of composites suitable for structural applications such as railway sleepers (Ju et al., 2020). In recycled polyethylene, reinforcement with sisal fibers increased the elastic modulus and altered the balance between stiffness and strength depending on fiber orientation (de Castro et al., 2020). Similarly, virgin–recycled blends at 50/50 ratios maintained good performance in rotomolding without penalizing impact strength (Cestari et al., 2021). Overall, these results highlight the importance of compatibilization and formulation design to expand the applications of recycled polymers in thermal molding processes.

Comparative studies between technologies, although less frequent, provide relevant evidence on the environmental and mechanical performance of processing alternatives. Garcia et al. (2021) demonstrated that, in the case of recycled ABS, fused deposition modeling (FDM) additive manufacturing presents a lower environmental impact for small batch sizes, whereas injection molding is more efficient and stable for larger-scale production. This highlights the importance of selecting a molding technology by considering factors such as batch size, energy consumption, and the required material properties, criteria that are also discussed in the literature on polymer processing (Polychronopoulos & Vlachopoulos, 2018).

In the category focused on process modifications and equipment design, the studies show that optimization of upstream stages and the redesign of molding systems improve the stability of thermal recycling. Sinchai et al. (2024) developed an automated injection system built from reused materials that incorporates laser detection to reduce overfilling and waste, demonstrating the potential of low-cost innovations for community-level contexts. Similarly, Singkronart et al. (2024) showed that the direct consolidation of incompatible waste without prior blending can reduce the typical embrittlement of immiscible systems, increasing deformation and fracture work compared to conventional melt-blended mixtures. Bashirgonbadi et al. (2022) evaluated the Quality Recycling Process (QRP), an enhanced semi-industrial-scale mechanical recycling process, reporting that the resulting regranulates exhibit

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improvements in mechanical properties such as ductility, flexibility, and impact resistance compared with conventional mechanical recycling.

Finally, studies on degradation and recyclability confirm that the performance of recycled materials is closely linked to their thermal and shear history. In PP impact copolymers, multiple re-injection cycles led to chain scission, oxidation, and a reduction in oxidation induction time, thereby decreasing the thermal stability of the material (Ji & Jung, 2023). Nevertheless, in certain cases, advanced recycling enables the production of regranulates with properties comparable to those of the original material, as observed for metallized films reprocessed using optimized techniques (Stachowiak et al., 2024). In weathered waste, Ronkay et al. (2021) reported that degraded materials can be processed using technologies such as injection molding, extrusion, or thermoforming after cleaning and sorting, while maintaining properties such as stiffness, albeit with losses in transparency, ductility, and fracture energy. These findings reinforce the importance of controlling shear, temperature, and mixing conditions to mitigate cumulative degradation during recycling cycles.

Overall, the results of this systematic review show that the performance of molded recycled polymers depends on the interaction between process parameters, formulation, degradation state, and prior conditioning strategies (such as extrusion). The evidence suggests that an integrated approach based on appropriate thermal control, compatibilization, reinforcement strategies, and improvements in recycling stages is essential to obtain high-performance recycled products and to advance toward more sustainable production systems.

5. Conclusions

This systematic review demonstrates that conventional thermal molding technologies continue to play a fundamental role in the transformation of recycled polymers, particularly those predominant in post-consumer waste such as PP, PE, and PET. The analyzed studies show that, despite the inherent variability of recycled materials, it is possible to obtain products with stable properties through appropriate processing, formulation, and prior conditioning strategies.

The findings underscore that molding efficiency and material performance do not depend on a single factor, but rather on the interaction between process parameters, compatibilization, reinforcement, and degradation control. Likewise, relevant advances are observed in equipment redesign and improvements in recycling stages, expanding the possibilities for industrial application of recycled polymers.

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Overall, the results highlight the importance of integrated approaches that link process control, materials engineering, and improvements in recycling stages to advance toward higher-performance recycled products, contributing to the transition toward a circular economy. Future studies should further explore systematic comparisons between molding technologies, as well as the development of more efficient additives and compatibilization strategies. In addition, it will be essential to expand evaluations to include energy consumption, operational stability, and process efficiency, key aspects for industrial adoption. Finally, there is a need to promote research that examines the behavior of recycled materials under real production conditions and contributes to the standardization of process parameters and characterization methodologies for more demanding applications.

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