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Radiation technology in polymer waste recycling and upcycling: mechanisms, applications, and prospects

Mirjana Ćujić*, Nataša Knežević, Filip Živković, Ljiljana Janković Mandić

University of Belgrade, "VINČA" Institute of Nuclear Sciences - National Institute of the Republic of Serbia, Mike Petrovića Alasa 12-14, 11351 Belgrade, Serbia

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ABSTRACT

Polymer waste represents a persistent environmental challenge, as conventional recycling methods often yield low-quality products and remain energy-intensive. Ionizing radiation, applied through gamma rays, electron beams, or X-rays, offers an alternative pathway for reprocessing and upcycling polymers. Radiation induces free radical formation, leading to two competing molecular transformations: chain scission, which lowers molecular weight and improves reprocessability, and cross-linking, which enhances mechanical strength and thermal stability. The outcome depends strongly on absorbed dose, dose rate, and irradiation conditions. Beyond molecular restructuring, irradiation can modify surface charge and polarity, enabling more effective sorting of mixed polymer streams. Reported applications include enhanced durability in rubber and polyethylene, improvements in food packaging films, and the production of wood–plastic composites with higher performance and market value. Comparative analyses indicate that, under optimized conditions, radiation-assisted recycling can match or surpass certain chemical methods in efficiency while delivering upcycled materials with extended service life. Current barriers include facility safety requirements, uniform treatment of heterogeneous waste, and integration into industrial recycling infrastructures. Future progress depends on pilot-scale demonstrations, dose–response optimization for common polymers, and comprehensive life-cycle assessments. These developments position radiation processing as a viable contribution to sustainable polymer waste management and the circular economy.

Keywords: radiation technology, polymer waste, wood-plastic composites.

1. Introduction

Polymer contamination has become a major concern because synthetic polymers, due to their inherent chemical stability and complex structures, resist natural degradation (Groh et al. 2023). Traditional recycling methods, particularly mechanical processes, often fall short when handling heterogeneous waste streams laden with contaminants, additives, and degradation by-products, which compromise the quality and industrial applicability of recycled materials. Furthermore, degraded polymer fragments and leached additives have been linked to harmful effects on terrestrial and aquatic ecosystems, with emerging evidence of potential human health risks (Zhang et al. 2024). Economic challenges, including high operational costs, market volatility of recovered polymers, and the need for advanced sorting and purification technologies, further exacerbate the inefficiencies of current recycling infrastructures (Uekert et al. 2023; Kolluru et al. 2024). This combination of environmental, health, and economic pressures underscores the urgent need for innovative approaches, such as radiation-assisted processing, for more effective decontamination and recovery.

In this study, our primary objective is to assess the transformative potential of ionizing radiation to enhance the recyclability of polymer waste and upcycle it into value-added materials. Drawing on recent insights that radiation-induced modifications, like chain scission, cross-linking, and grafting, can overcome the limitations of conventional mechanical and chemical recycling (Ponomarev 2020), we aim to demonstrate how these processes improve the quality and functionality of recycled polymers. This review distinguishes itself by highlighting radiation technology not merely as an alternative, but as a transformative advancement over mechanical and chemical recycling. By enabling controlled molecular modifications and surface functionalization, radiation offers a unique pathway to upcycle contaminated and degraded polymers – an area underexplored in prior literature. The paper is organized into sections on polymer waste issues, current

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* Corresponding author.
E-mail address: : cujicm@vin.bg.ac.rs (Mirjana Ćujić).

recycling technologies, fundamentals of radiation technology, and its applications in polymer recycling, and concludes with discussions and future perspectives.

2. Materials and Methods

Current waste management policies in the Republic of Serbia are increasingly aligned with EU directives, yet challenges persist in mitigating the environmental impact of polymer waste. National strategies set out in recent governmental reports emphasize reducing landfill dependency and promoting recycling initiatives ("Official Gazette of the Republic of Serbia" 05 Number 353-/588/2022-1 2022; Factsheet: Waste management in the Republic of Serbia 2021). Nonetheless, statistics show that about 78% of plastic packaging waste in Serbia is either landfilled or released into the environment (Popović 2020). Moreover, material flow analyses indicate that nearly 269,000 tons of plastic waste are disposed of in uncontrolled landfills each year, worsening environmental and health hazards (Vujić et al. 2010). Conventional recycling methods, hampered by contamination, inefficient sorting, and energy-intensive processes, struggle to recover quality polymers from heterogeneous, degraded waste streams (Sable et al. 2024). This mix of ambitious legislation and practical limitations highlights the need for innovative, technology-driven solutions to achieve a more circular and sustainable polymer waste management system.

The European Waste Framework Directive (2008/98/EC) sets the waste hierarchy, establishes end-of-waste criteria, and requires Member States to prioritize prevention, preparing for re-use and recycling, while implementing extended producer responsibility and targets for municipal and packaging waste, thereby framing national measures that seek higher recycling rates and quality recyclates. The EU Circular Economy Action Plan and related recent legislative packages (including rules on waste shipments, eco design and single-use plastics) further reinforce requirements for recycled content, improved sorting and traceability and restrictions on export of problematic plastic waste, creating a regulatory incentive to develop technologies that deliver higher-quality secondary materials and safer treatment routes. Radiation-assisted recycling and upcycling approaches can help meet these objectives by improving sorting, enabling controlled property restoration and supporting end-of-waste qualification for secondary materials ("Waste Management towards a more Circular Economy"; Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives).

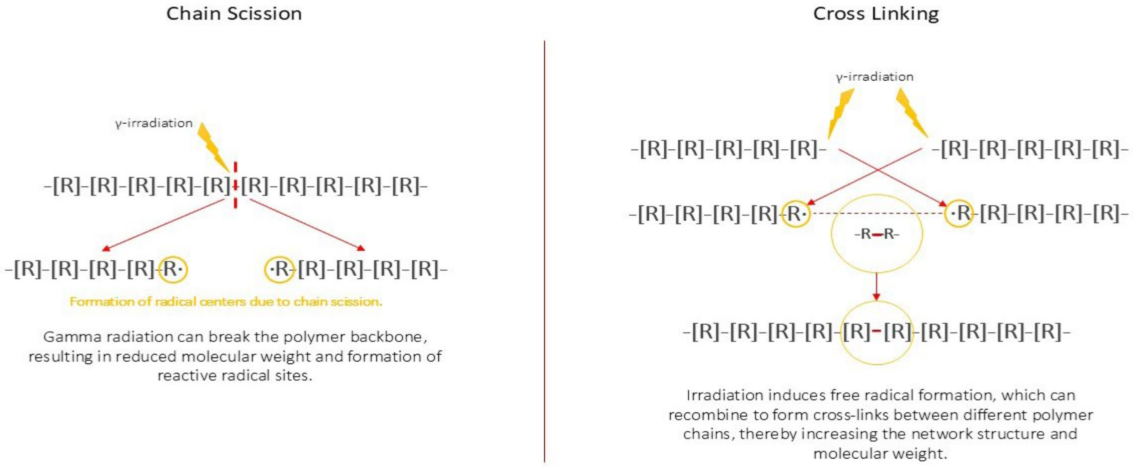
Current recycling technologies for polymer waste can be classified into mechanical, chemical, and advanced methods. Mechanical recycling relies on physical processes: sorting, washing, grinding, and remelting, and benefits from low energy requirements and established infrastructure. However, it is often limited by contamination, polymer degradation, and challenges in processing mixed streams (Babaremu et al. 2024). In contrast, chemical recycling (e.g, depolymerization, glycolysis, methanolysis) breaks polymers down into monomers or valuable chemical feedstocks, enabling recovery of high-purity materials but at the cost of being energy-intensive, capital-demanding, and sometimes yielding inferior products. Advanced methods like pyrolysis and catalytic cracking convert complex plastic wastes into fuels or chemical intermediates, yet they face economic and environmental challenges related to high temperatures, emissions, and product consistency (Ragaert et al. 2017). Against this backdrop, ionizing radiation stands out as a novel technology that, by inducing controlled chemical modifications (chain scission, cross-linking, and grafting), can enhance the recyclability of contaminated polymers, promote upcycling of degraded materials, and reduce energy consumption compared to conventional treatments. Radiation-induced recycling bypasses the need for solvents or high temperatures, offering a cleaner, more controllable process. It enables simultaneous decontamination and property enhancement, which conventional methods struggle to achieve. Preliminary investigations suggest that radiation processing not only improves material properties but also offers an environmentally benign alternative to thermal or chemical recycling.

2.1. *Fundamentals of Radiation Technology*

Ionizing radiation used in polymer processing arises from three principal sources: gamma rays, electron beams, and X-rays. Gamma rays are high-energy photons generated by the decay of unstable isotopes. With extremely short wavelengths (on the order of 10^{-10} meters or less) and remarkable penetration ability, they require dense shielding materials like lead or concrete for safety (Stark 2025). Electron beams consist of high-energy electrons produced by linear accelerators; their adjustable energies (typically 4–25 MeV) and interactions, dominated by Coulombic and inelastic collisions, allow for controlled energy deposition and surface modifications, making them ideal for applications demanding precise spatial dose control (Strydom et al. 2005). X-rays, generated when high-speed electrons decelerate upon striking a metal target (via Bremsstrahlung) or through atomic electron transitions, are electromagnetic waves with wavelengths ranging from 0.01 to 10 nanometers. While their ionizing behavior is similar to gamma rays, differences in energy distribution and production methods affect their penetration depth and interaction mechanisms within polymers (Stark 2025). Together, the unique energy spectra, penetration depths, and interaction modalities of these sources underpin their ability to induce specific molecular alterations. This versatility renders radiation technology a promising candidate to overcome conventional recycling limitations and advance sustainable practices in polymer waste management.

Ionizing radiation interacts with polymer chains to produce reactive free radicals that can trigger two competing processes: **cross-linking** and **chain scission**. Cross-linking forms covalent bonds between adjacent polymer chains, creating a three-dimensional network that increases molecular weight and rigidity. In contrast, chain scission breaks the main polymer chain, reducing molecular weight and often impairing mechanical properties. The balance between these processes critically depends on the irradiation dose and dose rate: at higher dose rates, rapid free radical formation promotes recombination and cross-linking, while lower dose rates allow radical diffusion and reactions (e.g., with oxygen) that lead to chain scission (Spadaro et al. 2017; Adamus-Wlodarczyk et al. 2018). The dose–response relationship is key to predicting irradiation outcomes, with parameters like the G-value quantifying cross-links and scissions. Spadaro et al. provide schematic dose–response curves delineating the impact of varying doses on chain bridging versus degradation (Spadaro et al. 2017). Comprehensive diagrams from electron beam studies clearly differentiate the onset of cross-linking from extensive chain scission (Adamus-Wlodarczyk et al. 2018; Chaudhari et al. 2023). Mechanism illustrations for these processes are shown in Figure 1.

Irradiation is emerging as a powerful tool to boost polymer recyclability by improving sorting and enabling upcycling. When exposed to ionizing radiation, polymers undergo surface chemical reactions that form free radicals and subsequently polar functional groups; these modifications enhance surface charge density and alter triboelectric properties, thereby facilitating polymer differentiation during sorting. For instance, low-energy ion irradiation can adjust the triboelectric characteristics of polymer films without compromising mechanical integrity (Dutta and Gohil 2023; Li et al. 2020). Moreover, the same modifications provide reactive sites for further functionalization, transforming degraded polymers into materials suitable for high-performance applications. Recent advancements indicate that these radiation-induced modifications can be incorporated into continuous recycling systems, offering a significant improvement over traditional methods. Detailed dose–response diagrams and kinetic models further support the optimization of these processes for industrial-scale upcycling (Mountanea et al. 2024).



Gamma radiation can break the polymer backbone, resulting in reduced molecular weight and formation of reactive radical sites.

Irradiation induces free radical formation, which can recombine to form cross-links between different polymer chains, thereby increasing the network structure and molecular weight.

Fig. 1. Mechanisms of Radiation-Induced Chain Scission and Cross-Linking in Polymer Packaging Waste

3. Results and Discussion

The process of polymer recycling starts with thorough pre-treatment to ensure homogeneity and eliminate contaminants. Waste plastics are sorted by type, washed, dried, and mechanically processed (e.g., granulated or pelletized) to create a consistent feedstock. Next, the prepared polymer is exposed to a controlled dose of ionizing radiation, via gamma rays, electron beams, or X-rays, in an industrial facility. This step is key, as radiation induces precise molecular modifications (chain scission and cross-linking) that tailor the polymer for reprocessing. Chain scission reduces viscosity by fragmenting long chains, while controlled cross-linking improves mechanical strength and thermal stability. The balance is determined by carefully calibrated dose rates and total absorbed doses (Dutta and Gohil 2023). Following irradiation, post-treatment processes like thermal stabilization and extrusion quench residual free radicals and consolidate the modifications, effectively converting degraded or mixed waste into a reformulated product with enhanced performance and upcycling potential. This integrated approach not only overcomes the limits of traditional recycling but also shows how radiation technology can transform the circular economy for polymers (Walo and Rzepna, 2020).

3.1. Application of Radiation in Polymer Recycling

Radiation modification has been applied across diverse polymer systems to enhance material performance in various industries. For instance, in the tire industry, electron beam irradiation induces partial cross-linking in rubber formulations, improving tensile strength, abrasion resistance, and durability in both radial tires and inner tubes. In a recycling scenario, mechanically devulcanized crumb rubber is first cleaned and homogenized, then exposed to an electron-beam dose calibrated to reduce low-molecular-weight degradation products and rebalance network defects – the result is crumb or reblend pellets with improved tensile strength and abrasion resistance suitable for use in engineered rubber goods, sporting surfaces or higher-value rubber blends. Radiation-assisted treatment reduces the need for fresh additives, lowers volatile degradation residues, and can be combined with compatibilizer grafting to incorporate mixed elastomer streams into composite products (Banerjee et al. 2023; Scagliusi et al. 2023). Likewise, instead of only producing virgin PEX by irradiation, the same principles enable upcycling of degraded or mixed PE waste into PEX-like or partially cross-linked products. The production of cross-linked polyethylene (PEX) pipes, commonly used in hot water distribution, relies on irradiation to form robust three-dimensional networks that boost thermal stability and mechanical resilience. For feedstocks where excessive chain scission has occurred, a two-step route – irradiation for controlled scission to lower melt viscosity, followed by reactive extrusion with multifunctional monomers and a secondary irradiation step to form stable cross-links – creates reprocessed materials suitable for non-pressure pipe applications, construction profiles, or wood-plastic composite matrices with improved service life (Maguire, Krarti, and Fang 2011). In food packaging, treatments with gamma rays and electron beams modify materials such as kraft paper and poly(lactic acid) (PLA), enhancing surface properties, barrier performance, and shelf life through controlled alterations in polymer microstructure. Radiation processing can convert contaminated, multi-layer, or degraded packaging films into higher-value products rather than downcycling to low-grade applications. For biodegradable PLA film waste, carefully controlled irradiation can improve barrier and mechanical properties via cross-linking or enable grafting of hydrophobic chains to extend service life in multilayer structures (Silvestre et al. 2017; Grosvenor et al. 2022; Irimia and Enache 2020). These examples underscore how radiation modification not only facilitates the upcycling of challenging waste streams but also drives the creation of high-performance, sustainable polymer products. Radiation processing of polymer waste offers significant technical and economic advantages by transforming waste into high-value products. Controlled irradiation enhances molecular characteristics, yielding superior mechanical properties and extended service life, which translates into higher market value compared to conventional downscaling that produces lower-quality materials. Life-cycle assessments and cost–benefit analyses show that, even accounting for additional energy inputs, improved durability, reduced environmental footprint, and premium pricing of upcycled products more than offset the costs. For instance, studies on wood-plastic composites report sizable savings in greenhouse gas emissions and energy consumption, along with reduced reliance on virgin polymers (Malviya, Purohit, and Singh 2021; Khan et al. 2021). Moreover, recent IAEA research demonstrates that radiation-based recycling can convert post-consumer waste into commercially viable, sustainable products, shifting the economic paradigm toward value-added materials.

The application of radiation technology in polymer recycling faces several challenges. Safety is a major concern, as handling high-energy gamma rays, electron beams, or X-rays requires specialized facilities with robust shielding, strict regulatory oversight, and rigorous safety protocols (Clough 2000). Moreover, the substantial energy input needed for irradiation, especially if not powered by renewables, raises questions about process efficiency and environmental impact, while scaling from laboratory to industrial operations demands overcoming engineering challenges such as uniformly treating heterogeneous waste streams and integrating these processes into existing recycling infrastructures (Uekert et al. 2023; Martínez-Barrera et al. 2015).

Despite the issues, radiation-assisted recycling offers clear advantages. It precisely induces chain scission and cross-linking, enabling controlled modifications that enhance mechanical properties and processability compared to conventional mechanical or chemical methods (Dutta and Gohil 2023; Clough 2000). Its versatility also allows treatment of a broader range of polymers, including temperaturesensitive or significantly degraded ones, thereby addressing material heterogeneity (Uekert et al. 2023). Compared to mechanical recycling, which often results in downcycled materials, and chemical recycling, which involves complex reaction pathways and high energy input, radiation processing stands out for its ability to tailor polymer properties through dose-controlled reactions. This dual capability – recycling and upcycling – positions radiation technology as a next-generation solution for polymer waste management.

Below, in Table 1, is an overview of energy consumption data from several studies comparing recycling methods. Although the exact numbers depend heavily on technology design, scale, and operating conditions, many life cycle assessment (LCA) studies provide the following approximate ranges:

Table 1. Comparative Energy Consumption of Polymer Recycling Technologies

Recycling Technology	Energy Consumption (MJ/kg)	Remarks
Mechanical Recycling	2-4	Involves low-energy mechanical processing, such as sorting, washing, and re-melting, with minimal chemical or thermal transformation.
Radiation-Induced Recycling (Gamma Irradiation)	6-15*	Energy demand depends on the dose needed for effective chain scission or cross-linking; when optimized, it compares favorably with chemical methods.
Chemical Recycling	15-50	Processes like solvolysis or catalytic cracking require high temperatures and complex reaction pathways, leading to higher energy usage.
Advanced Recycling (Pyrolysis/Gasification)	20-60	These techniques operate under elevated temperatures; energy consumption can fluctuate significantly based on reactor design and process integration.

* Data for radiation-induced processes are less abundant in the literature than for conventional routes, so the numbers shown in the table are just an approximation, but several reports on polymer modifications via gamma irradiation indicate that—with optimized conditions—the process can be competitive with chemical recycling in terms of energy input.

The energy ranges shown in Table 1 should be interpreted alongside life-cycle outcomes rather than as standalone performance indicators. Energy input for a recycling route must be compared with avoided impacts from displaced virgin production, extended product lifetime through upcycling and changes in end-of-life emissions – recent reviews emphasize that cradle-to-grave LCA boundaries and consistent system assumptions are essential for meaningful comparisons (Ramesh and Vinodh 2020).

Life-cycle assessments show that higher process energy for advanced routes can be justified when the process yields higher-quality recyclates, enables substitution of virgin feedstock, or extends service life through upcycling. Comparative LCA work stresses the need for consistent system boundaries, credits for avoided production and sensitivity analyses on energy sources, because radiation-based treatments powered by low-carbon electricity or integrated into circular product chains can produce net environmental benefits despite modestly higher per-kg energy use (Ramesh and Vinodh 2020; Kerps et al. 2024; Rajendran 2020). Looking ahead, future research should optimize irradiation parameters such as dose, dose rate, and exposure time to selectively induce desirable chemical modifications without causing excessive degradation. Efforts must focus on developing pilot- and industrial-scale models that integrate radiation processing with current recycling systems and on conducting detailed life-cycle assessments and techno-economic analyses to mitigate environmental and safety impacts. This roadmap will transition radiation technology from laboratory innovation to a viable, sustainable solution for the circular economy in polymers (Dutta and Gohil 2023; Clayton et al. 2025).

4. Conclusion

Ionizing radiation provides a controllable means of restructuring polymer waste, with the potential to overcome limitations of both mechanical and chemical recycling. By regulating irradiation parameters, polymer chains can be selectively cleaved or cross-linked, producing materials with properties tailored for reprocessing or for advanced applications. Modifications to surface charge further support improved sorting of mixed plastic waste, which remains a major barrier in current recycling systems. Demonstrated applications across packaging, piping, and composite production highlight the versatility of this approach. Remaining challenges relate primarily to safety standards, process uniformity, and industrial scalability, but these can be addressed through systematic pilot studies and integration with existing recycling infrastructure. Broader adoption will rely on rigorous techno-economic and environmental assessments that verify competitiveness with established methods. With these foundations in place, radiation technology holds considerable promise as a tool for transforming polymer waste streams into durable, higher-value products within a circular economy framework – by overcoming the limitations of mechanical and chemical recycling, radiation technology emerges not just as a viable alternative, but as a superior strategy for sustainable polymer waste valorization.

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