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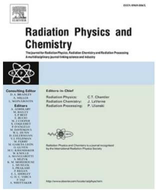

Recycling of polymers by ionizing radiation: the potential applications of radiation-induced effects in polymers – a review

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ABSTRACT

One of the most pressing issues of our time is the proper management of waste generated by society, as it significantly harms the living environment. Plastic waste is no exception; due to its structure, it decomposes slowly, and the resulting microplastics also pose a threat to living organisms. The problem of recycling plastic products at the end of their life has not yet been fully solved. As a result most of them end up in landfills, preventing the establishment of a circular economy. Therefore, it is crucial to develop new, economically viable technologies. Ionizing radiation produces several effects in polymers such as chain scission, cross-linking, functionalization, grafting, and electrical charging, making their application in plastic waste recycling an increasingly researched area. Polymers that cannot be sorted with conventional technologies (first step in proper recycling) can be selectively separated by radiation-assisted sorting. Ionizing radiation treatment can improve the mechanical properties of waste mixtures containing polymers and can be used to produce cross-linked or high-molecular-weight materials, significantly aiding the efficient recycling of polymers. Thus, ionizing radiation can be applied in recycling plastic products that have reached the end of their life cycle, thereby contributing to the development of a circular economy.

1. The state of plastic waste recycling: challenges to be addressed

One of the most significant problems in our society nowadays is the proper management of waste generated (Zorpas, 2020; Khan et al., 2022; Demirbas, 2011). Among these, plastic waste (Idumah and Nwuzor, 2019; Simon-Stőger et al., 2019) plays a prominent role, as only a small portion is effectively recycled (Fig. 1). As a result, plastic waste causes various environmental issues. Synthetic plastics degrade very slowly and gradually break up into small particles, including microplastics, which pose a great risk to the environment (Alhazmi et al., 2021). Most commonly, plastic waste ends up in landfills, or in worse cases, they are illegally dumped in unauthorized locations or find their way into the oceans. Energy recovery also plays a significant role in the end-of-life management of polymer products, as they possess high calorific value. However, their incineration generates a large amount of environmentally harmful substances, requiring advanced filtration systems. It is also important to note that in these cases, the secondary recycling of the materials will not take place, which hinders the development of a circular economy. Therefore, this is not a preferred utilization route (Dutta et al., 2023; Ponomarev et al., 2022; Ignatyev et al., 2014; Toyen et al., 2024).

Of course, this causes numerous problems, as harmful substances can dissolve from plastic wastes, which can enter deeper water layers and agricultural lands and eventually even appear in humans, causing various short- or long-term health issues (Pandey et al., 2023). Another hazard of dumping in the environment is that plastics are capable of easily catching fire, and extinguishing them is very challenging, and as a result, pollutants are released into the air without filtration (Nadal et al., 2016). This is particularly common in waste tire landfills, where these fires are almost impossible to put out and can burn for several days or even years (Xiao et al., 2022). Examples of such incidents are the fires in Kuwait and in Bradford, where it took over a week to extinguishing the fire. The longest-burning tire dump fire lasted for nearly 15 years in Wales, where more than 10 million waste tires were stored (Alsulaili et al., 2021; https://autoily.com/how-long-do-tires-burn/, 2025).

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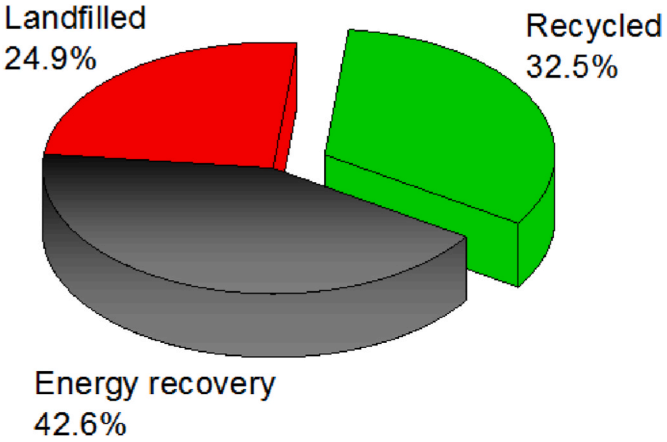

Fig. 1. Plastic waste management in the European Union (based on EuroStat) (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Waste_treatment, 2024).

One problem in the recycling of plastic waste comes from the non-product-specific collection of plastic waste in many countries. However, there are some countries, where the collection rate is high and collection is product-specific (Bishop et al., 2020). The European Union has various directives specifying (e.g. Green Deal) the percentage of these materials that each country should recollect. In this case, there are multiple options for the recycling of plastic waste (Eckert and Kovalevska, 2021; Toldy, 2025). The recycling of plastic waste can be divided into four categories such as primary, secondary, tertiary and quaternary recycling (Table 1.) (Al-Salem et al., 2009). One of the simplest methods is quaternary recycling, where energy is recovered from plastic waste by incineration (Turer and Achilias, 2012; Rowhani and Rainey, 2016; Singh et al., 2009). However, this recycling method disrupts "circularity" as the raw materials are permanently lost, and the generated carbon dioxide (CO_2) also increases the greenhouse effect (Sathiskumar and Karthikeyan, 2019). Another issue is that without ensuring proper combustion conditions and filtration systems, toxic substances can be released into the environment. Tertiary recycling (Schwarz et al., 2021; Fox and Stacey, 2019) has a high potential as heterogeneous and contaminated plastic waste can be used as feedstock. It converts plastic waste into smaller molecules (Martínez et al., 2013; Paradela et al., 2009) and enables the production of chemicals, fuel and polymers or other materials, like carbon nanotubes (Williams, 2021; Wu et al., 2022). The produced heat and steam can be used for other processes. Nevertheless, the costs are high and an energy intensive purification of products is required (Hita et al., 2016). Electron beam–assisted pyrolysis provides a number of important advantages. These are lower processing temperatures and heating power as well as a reduction of CO_2 emission, a higher yield of liquid products and a lower amount of gases and char (Mirzazade et al., 2023). Primary recycling (Al-Salem et al., 2009; Schwarz et al., 2021; Singh et al., 2017; Ragaert et al., 2017) is mainly used in the manufacturing of plastic products as the recovered material is reused for the original application (closed loop recycling). Secondary recycling (Lei et al., 2007) is the most common type of plastic waste recycling. It is limited to thermoplastic waste and is a greater challenge, as thermoplastic waste is mixed and its composition is rarely known. Also, the performance of recycled thermoplastics is reduced with each additional melt processing (Schwarz et al., 2021).

Table 1
Overview of primary, secondary, ternary and quartenary plastic waste recycling routes (based on Al-Salem et al. (2009)).

Recycling category	Alternative term	Principle	Advantages	Limitations
Primary recycling	Closed-loop recycling	Recovered materials are reused in the same application for which it was originally produced	Lower energy demand, preserves the material properties	Strict requirements on polymer type and purity
Secondary recycling	Mechanical recycling	Reprocessing using melt processing technologies (extrusion, injection moulding)	Can be used for the majority of thermoplastic waste	Progressive degradation of properties with each cycle
Ternary recycling	Chemical recycling	Conversion of waste polymers into monomers, fuels or chemical feedstocks	Broad tolerance, production of high value chemicals, fuels and materials	High capital and operation costs, energy intensive purification tehcnologies
Quatenary recycling	Energy recovery	Recovery of energy from plastic waste through incineration	Simple process, significant reduction of plastic waste	Loss of material resources, CO_2 emissions and potential release of toxic substances

Of course, one of the most important aspects is prevention, which starts right from the design phase (design for recycling) and is especially important for packaging materials (Reuter, 2011; Ding and Zhu, 2023). There are many reusable plastic packaging products such as rigid-walled bottles that can be refilled and used multiple times. Unfortunately, there is great variety in design and the usability of certain products is limited, such as blister packaging or products that, for food safety reasons, need to be single-use. Many challenges need to be addressed in developing efficient recycling processes for the transfer to a circular economy (Babaremu et al., 2022). The integration of radiation technologies into existing recycling processes present novel opportunities for environmental rehabilitation, material innovation and resource sustainability (Ponomarev et al., 2022).

Secondary recycling includes the subprocesses of collection, cleaning, shredding, sorting, and compounding (Dutta et al., 2023). Sorting is particularly important as the melt mixing of different polymer "families" lead to final products with reduced mechanical performance due to incompatibility (Silva and Wiebeck, 2020). Separation principles work in various ways, with density-based separation being the most common, although it has certain limitations. In the case of polyolefins, polyethylene (PE) and polypropylene (PP) cannot be separated with this method (Silva and Wiebeck, 2020). An excellent technique for separating them is the use of electron treatment, which exploits the principle of charge differences (Ponomarev et al., 2022; Albrecht et al., 2016). The last stage entails manufacturing the product with an appropriate melt processing technique (e.g. extrusion, injection moulding, etc.) (Kun et al., 2024). Often, the waste is mixed with a certain amount of fresh material (often referred to as matrix) to minimize the degradation of the properties of the final material. However, the adhesion between the enclosing matrix and the waste polymer is often inadequate, resulting in reduced mechanical performance of the final product (Ignatyev et al., 2014). Various methods are used to address this, including different chemical treatments in many applications, which can be harmful to the environment (Dutta et al., 2023). Ionizing radiation can provide a solution to these problems, and in the following sections, radiation-assisted recycling methods are discussed in detail.

2. The economic aspects of polymer recycling

In our society, it is necessary to prioritize the circular economy over the traditional linear economy based on single-use consumption, as only the former is sustainable in the long term. This model primarily serves the protection of environment. However, it also helps to reduce the dependence on raw materials, which is crucial in the long term, as these resources are being depleted (Gubanova et al., 2019; Valerio et al., 2020). Of course, this transfer requires time and solutions that have to take into account economic, environmental, social and technological aspects. In the European Union and other regions, the adoption of the so-called 4R (reduce, reuse, recycle, and recover) framework is beginning to spread (Okan et al., 2019).

In the case of plastic waste, it is important to replace single-use products with those that can be used multiple times (reduce, reuse), thereby reducing the amount of waste that ends up in the environment. Of course, these reusable products will also wear out over time, and it is practically unavoidable to recycle them at the end of their life cycle. The essence of the circular economy is everything that can be recycled is recycled. They should be reused, recycled or recovered in an open or closed cycle for new valuable products. Therefore, as previously mentioned, quaternary recycling also called energy recovery is not sustainable. However, the cost-efficient up-recycling of plastic waste is a huge challenge as mixed and/or contaminated plastic wastes with unknown composition have to be processed. New technologies have to be developed that meet the requirements of the circular economy, and have to be environmentally friendly and economically viable as well. The latter can be verified by using economic and life cycle assessment tools. This is needed to ensure that plastic products prepared from recycled plastic waste are competitive and have a lower environmental impact (e.g. CO_2 footprint) compared to those made from virgin polymers. Unfortunately, in most cases, some pre-treatment is required to properly recycle the plastic waste. This often involves various chemical treatments or additives, which are not environmentally friendly or economically viable. These materials need to be post-processed or disposed of.

Radiation technologies fulfil the key principles of “green” chemistry and enable manifold possibilities in the preparation of plastics using controlled cleavage or the formation of chemical bonds (Ponomarev et al., 2022). They are comprehensively proven for the preparation of high-performance polymeric compounds and for recycling of some specific plastic waste. Ionizing radiation treatments offer new approaches for sustainable recycling technology. It can reduce the amount of harmful additives, solvents, and can even save energy. The latter is particularly important from an economic perspective (Dutta et al., 2023). In the case of radiation technology, the investment costs depend primarily on the type and power of radiation source, while the operational costs depend significantly on the throughput. Both costs can be evaluated with the Excel-Based Economic Assessment Modelling (EBEAM) tool, developed by the International Atomic Energy Agency (IAEA) (Ponomarev et al., 2022).

The IAEA launched the coordinated research project on “Recycling of Polymer Waste for Structural and Non-Structural Materials by using Ionizing Radiation” within the “NUTEC plastic” initiative. In this project, 55 IAEA member states are collaborating in three regional Technical Cooperation Projects on the development of novel radiation-assisted recycling processes for plastic waste. These coordinated activities encompass a wide range of national research centres, pilot-scale facilities and laboratories across different regions, including university-based research groups, national irradiation facilities (electron beam and gamma), and applied research centres focusing on polymer processing and recycling. The priority areas are radiation-assisted secondary (mechanical) recycling for the production of rubber particle–filled composites and wood–plastic composites and radiation-assisted tertiary (chemical) recycling as well.

Fig. 2 shows two options for the integration of radiation technology into existing recycling processes such as secondary and tertiary recycling. This article focuses on secondary recycling. After collection and transportation, some pre-treatments such as washing and sorting are required before compounding and the production of plastic products from recycled plastic waste. Sorting is required to enhance the mechanical properties of the new products. The use of radiation technologies before compounding results in the enhanced sorting of polyolefin mixtures or compatibilizing compound components for improved interfacial adhesion.

3. Interactions between ionizing radiations and polymers

Radiation that possesses sufficient energy to ionize atoms and molecules is called ionizing radiation. We can encounter ionizing radiation in our everyday life, which can occur naturally (cosmic or terrestrial radiation) or originate from artificial sources (medical applications, nuclear energy, etc.). To effectively use ionizing radiation in recycling, its effects on polymers need to be clarified, which we will discuss later on. (Chmielewski and Haji-Saeid, 2004; Drobny and Drobny, 2013).

There are two types of ionizing radiation: particle and electromagnetic radiation. The energy of particle radiation comes from the kinetic energy of particles such as protons, neutrons, electrons, alpha particles, and heavy ions). Particle radiation is also often referred to as particle beams. In the case of polymer processing, electron beams (EB) are used most commonly for recycling. The electromagnetic radiation most commonly used for recycling plastic waste is gamma radiation (mainly ^{60}Co). It is generated during the radioactive decay of excited atomic nuclei. In industrial radiation facilities, the isotopes ^{60}Co and ^{137}Cs are used as gamma radiation sources, but the former is far more common (Drobny and Drobny, 2013; Wojnárovits, 2007).

The primary effect of ionizing radiation is based on the excitation and ionization of atoms and molecules (Fig. 3) along the track of the incident ionizing radiation (Singh et al., 2009; Sathiskumar and

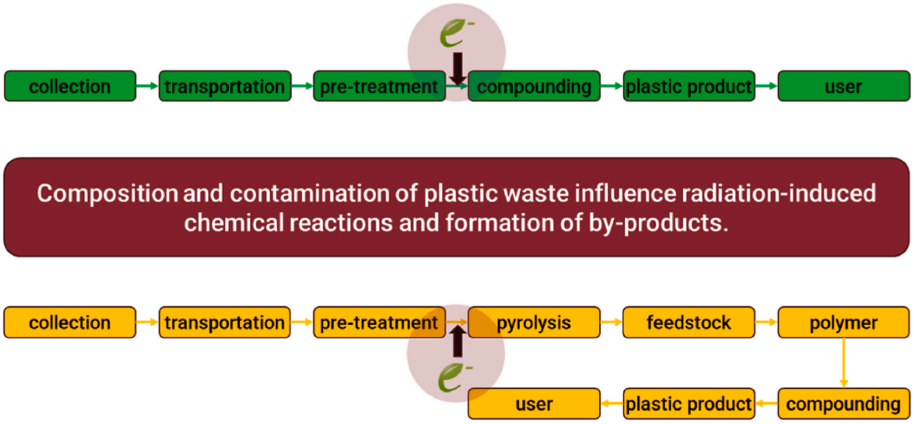

Fig. 2. Options for the integration of radiation technology into existing recycling processes.

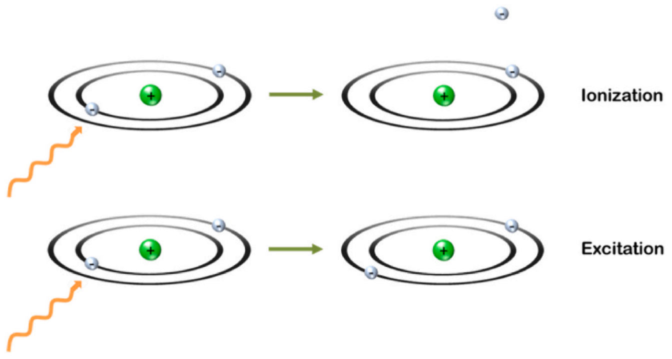

Fig. 3. Ionization and excitation of atoms by ionizing radiation.

Karthikeyan, 2019; Schwarz et al., 2021). When the transferred energy is greater, an electron can be ejected, and the atom becomes ionized. If the energy is not sufficient for ionization, the electron moves to a higher energy level, resulting in excitation (Fig. 3).

Afterwards, the ionized and excited molecules transfer into polymer radicals (Fox and Stacey, 2019). Finally, they initiate complex chemical reactions and lead to structural changes of the polymer. Examples of such reactions are polymerization, cross-linking, chain scission and oxidation of polymers and so on. (Fig. 4) (Drobny and Drobny, 2013; Tavernier, 2010; Hubbell, 1999; Keizo et al., 2012; Tamada and Kudo, 2018; Datta et al., 2024).

The cross-linking of polymers is one of the main application of ionizing radiation. The formation of cross-links (Fig. 4), where intermolecular covalent bonds are formed between polymer chains lead to the formation of a three-dimensional network. This process will hinder the recycling of plastics by secondary recycling, but it can be used for enhanced interfacial adhesion between different phases of the finished products (Drobny and Drobny, 2013; Tamada and Kudo, 2018; Cleland et al., 2003; Burillo et al., 2002).

However, due to the high energy of ionizing radiation, the covalent bonds in the polymer's main chain may also break (Fig. 4), which is a degradation process. In the case of elastomers and other three-dimensional cross-linked systems (e.g. resins), selective breaking of the network bonds (devulcanization) can be a beneficial process for their recycling (Tamada and Kudo, 2018; Cleland et al., 2003; Kiss et al., 2022).

In a radiation treatment at a low dose rate and in the presence of air, the generated primary radicals can react with oxygen or the generated ozone (Fig. 4). The reaction with oxygen leads to the formation of highly reactive peroxyl radicals, which can further react and form various hydroperoxides. However, hydroperoxides are not stable for long and can decompose, creating new radicals and initiating new reactions. These reactions can result in the formation of cross-links or graft-links, chain scission, and various functional groups containing oxygen such as carboxylic acids, ketones, esters or hydroxyl groups. These groups are potentially prone to reactions; they can form ester-, amide-, and urethane covalent bonds thereby improving the connection between phases. These transformations can improve the compatibility between waste polymers, and additives and fillers, leading to enhanced properties of the final material. It is also important that oxygen can diffuse into the polymer material as well (not just react on the surface) causing reactions that can degrade the backbone, but this can be controlled with the dose rate (Drobny and Drobny, 2013; Kiss et al., 2022; Kornacka et al., 2017; Khusyainova et al., 2022; Colom et al., 2007).

Finally, grafting reactions are also possible (Fig. 4), where a new monomer polymerizes onto the chain with the help of ionizing radiation. This technology can produce good compatibility during recycling if a monomer similar to the matrix polymer is grafted onto the recycled plastic waste. Maleic anhydride (MA) is commonly used for this purpose since it enables the incorporation of polar functionality into inherently nonpolar materials, thanks to the presence of three oxygen atoms in the acid anhydride (Drobny and Drobny, 2013).

The type of the aforementioned radiation-induced reactions (cross-linking, chain scission, oxidation and grafting) depends on several parameters, including the structure of the polymer, environmental conditions (atmosphere, temperature), as well as the absorbed dose and the dose rate. Irradiation of polymers in the presence of oxygen facilitate oxidation and degradation. Thus, tailored cross-linking or grafting applications require an oxygen-free atmosphere and/or a high dose rate. The latter is advantageous for cross-linking as the generation rate of radicals is far higher than the oxygen diffusion rate into the polymer material. It is important to consider this aspect, as industrial electron beam facilities operate at higher dose rates than those of gamma ray sources, making it more suitable for cross-linking, while gamma radiation is more suitable for oxidation (Keizo et al., 2012).

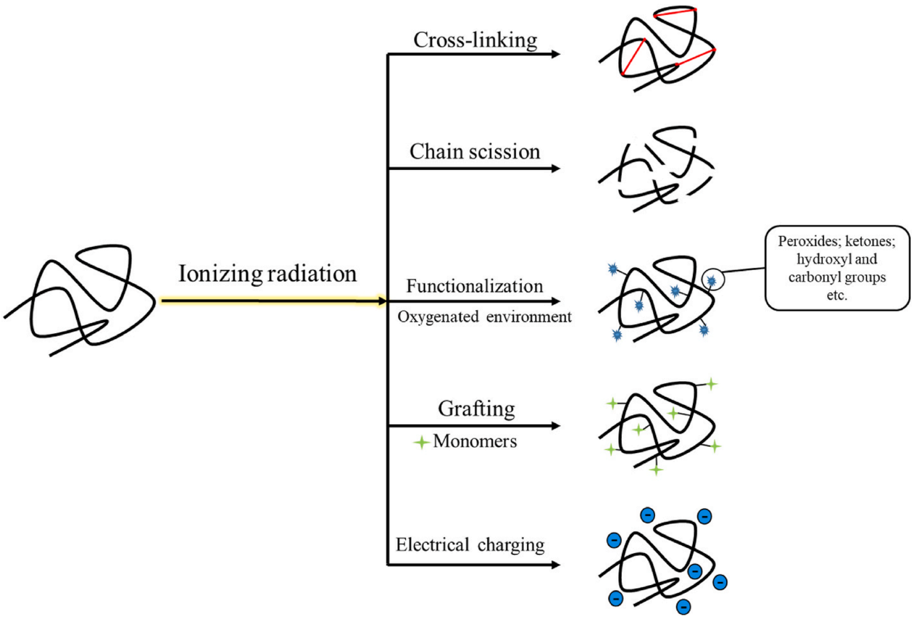

Fig. 4. Main effects in polymers by ionizing radiation.

4. Recycling options for polymers, grouped according to the leading effects of ionizing radiation

4.1. Interfacial grafting (graft-links between the phases)

The interfacial grafting (cross-linking between phases) of polymers with the aid of ionizing radiation is a very important technique for the recycling of polymers. End-of-life thermoplastic polymers are collected and separated with different methods, and after that, they are mostly ground, resulting in small-sized granules. These can be re-processed by adding them into virgin materials and using injection moulding or extrusion, but the problem is that the mechanical performance of the plastic products will not be adequate due to low interfacial adhesion. Interfacial grafting can improve mechanical performance, which extends the application possibilities of these materials. Interfacial grafting can be performed with various methods using different chemical agents such as sulphur or peroxides (Wagenknecht et al., 2006). New covalent bonds between the different phases can also be formed with ionizing radiation in the presence of interfacial cross-linking agents (Sritragool et al., 2010; Czvikovszky, 2003).

This mechanism helps to recycle various kinds of cross-linked plastic waste as well (rubbers, thermosets etc.). Due to cross-linking, they cannot be modified by melt processing, which makes it really hard to recycle them. When end-of-life tires are recycled, they are most commonly ground first (Yerezhep et al., 2021; Colom et al., 2024). This ground tire rubber (GTR) is incorporated into a thermoplastic polymer matrix (Simon-Stőger and Varga, 2021), which can later be used for the manufacturing of new products. However, the mechanical performance of these GTR-filled polymers is inferior for high-performance applications (Haq et al., 2025; Rodak et al., 2024). Using ionizing radiation and a suitable cross-linking agent, interfacial adhesion between the GTR (or any other cross-linked waste polymer) and the polymer matrix can be improved, which significantly enhances mechanical properties (Sritragool et al., 2010).

The examples shown in Table 2 clearly demonstrate that radiation-induced interfacial grafting can be used for the recycling of different plastic materials. It is possible to use thermoplastics in combination with fillers produced from cross-linked plastic waste when they reach the end of their life. Using this technology, the mechanical performance of products prepared from recycled plastic waste can be enhanced. This extends the fields of application and reduces the amount of plastic waste in the environment. It can be done by electron-beam treatment or ^{60}Co irradiation as well. The required dose is usually less than 100 kGy, which makes this process economically feasible.

4.2. Degradation by the breaking of main chains

Radiation-induced degradation of plastics can lead to the breaking of main chains, a changed conjugation of bonds as well as the forming of additional functional groups and volatile products. This effect can be enhanced by irradiation in an oxygen atmosphere. Examples of radiation-induced degradation are polytetrafluoroethylene and post-consumer tire rubber. Due to their intermolecular bonds, cross-linked rubbers cannot be re-processed at the end of their life cycle like thermoplastics with conventional melt-based technologies (e.g. extrusion or injection moulding). One possibility of recycling rubber waste is the selective breaking of the cross-links with a method that effectively recovers the original raw material, called devulcanization. Of course, this is a challenging task, especially because the necessary selectivity is difficult to set, most methods result in the breaking of not only the cross-links but also the backbone itself (degradation), which is undesirable for reuse (Simon et al., 2020; Saputra et al., 2021; Edwards et al., 2016). However, with the help of tailored irradiation, it is possible in some cases to selectively break only the bonds between the chains, with minimal degradation. Some studies have already explored this technology, in the field of rubber recycling (Kiss et al., 2022; Karger-Kocsis et al., 2013).

Another established application of radiation-induced chain scission is the recycling of polytetrafluoroethylene (PTFE). It is not meltable and cannot be re-processed with conventional melt-based technologies, thus, new technologies are needed. Ionizing radiation can effectively reduce the molecular weight through chain scission, allowing these materials to be re-processed into new and valuable products (Ponomarev, 2020; Lunkwitz et al., 2000). The main aim of radiation-assisted degradation is the production of micro-powders that can be used as a high-value additive in paints, oils, greases and polymers. PTFE micro-powder has a high market value, which makes the radiation-assisted degradation of PTFE waste attractive.

Another potential application of radiation-assisted recycling using main chain scission is the radiolytic degradation of various cellulose wastes. It produces useful products such as yeast, glucose, bioethanol, and similar compounds. In this case, radiation is a simple and advantageous method to 'convert' large amounts of waste into valuable materials and reducing their environmental impact (Ponomarev, 2020; Saini et al., 2015; Gryczka et al., 2014; Kumar et al., 2009; Ponomarev and Ershov, 2012). Examples for the recycling of polymer waste using chain-scission are presented in Table 3.

As was previously mentioned, the main applications of chain scission in plastic waste recycling are the treatment of cross-linked plastic waste, PTFE and natural polymer waste. With chain scission, the plastic waste can be pre-treated for reprocessing. In this case, both ^{60}Co radiation and electron beam irradiation can be used. However, the required doses are high (>100 kGy).

4.3. Grafting

During the recycling of post-consumer products, it is most common to produce flakes or particles from thermoplastics or cross-linked products to be used for the preparation of high-performance plastic compounds. However, in many cases, the interfacial adhesion between the components of the compounds is inadequate, resulting in low mechanical performance of the finished products.

One possible method to enhance interfacial adhesion is grafting, where monomers are chemically attached (via covalent bonds) to polymer backbones as side chains, thereby increasing their surface activity and alter their polarity. These modifications enhance the interfacial adhesion between the components of the compound via additional physical and chemical interactions (Czvikovszky, 1995, 1996). A typical example is the grafting of maleic anhydride to polypropylene or polyethylene for the production of MA-grafted PP or PE. Grafting with maleic anhydride is frequently used for polymers that are incompatible with polyolefins or other hydrophobic polymers (e.g. GTR) to ensure enhanced adhesion between phases of the compound, thus broadening the field of applications.

Besides various other methods, ionizing radiation is widely used. Three different grafting techniques are used in radiation-induced grafting: the simultaneous, peroxide, and pre-treatment method (Chapiro, 1977; Enomoto et al., 2011; Saito et al., 1999; Wojnárovits et al., 2010). The simultaneous method is characterized by irradiating the polymer in the presence of the monomers resulting in the formation of non-grafted homopolymers. In the case of the pre-treatment and the peroxide method, the formation of radicals is separated in time from the grafting reaction. Radiation-induced grafting is a widely tested and used procedure for grafting without any contamination from initiators (Vahdat et al., 2007; Baranowska et al., 2024).

By radiation-induced grafting, various functional groups can be generated onto the surfaces of films, flakes, membranes and particles. Thus, tailored materials can be prepared for the selective capturing of different ions, contaminants, dyes, etc. This is particularly important in wastewater treatment (Wojnárovits et al., 2010), as these materials can capture pharmaceutical residues or other harmful heavy metal ions that are dangerous to human health. They can also be used for purifying flue

Table 2

Examples of interfacial grafting used in the recycling of plastic waste.

Materials	Radiation source	Applied doses (kGy)	Test to confirm modification	Attained properties	Reference
Ethylene-propylene-diene monomer (EPDM)/GTR/high-density polyethylene (HDPE)	^{60}Co	50, 100, 150, 200, 250	Soxhlet extraction, thermogravimetric analysis (TGA), mechanical tests	Increased gel content, tensile strength and modulus increased up to 150 kGy	Abou et al. (2008)
EPDM/GTR	Electron beam	25, 50, 75, 100	Soxhlet extraction, mechanical tests	Increased gel content and hardness up to 50 kGy, improved tensile strength and elongation at break	Yasin et al. (2012)
Ethylene-vinyl acetate (EVA)/GTR	Electron beam	50, 100, 150, 200	Soxhlet extraction, transmission electron microscopy (TEM), differential scanning calorimetry (DSC), dynamical mechanical analysis (DMA)	Increased gel content, increased storage modulus, with same damping properties	Ramarad et al. (2017)
Low-density polyethylene (LDPE)/GTR/EVA	Electron beam	50, 100, 150, 200	Mechanical tests (cyclic), DMA	Increased tensile strength (higher for blends containing EVA), increased perforation energy	Mészáros et al. (2012a)
PP/GTR	^{60}Co	25, 50, 75, 100	Fourier transform infrared spectroscopy (FTIR), mechanical tests	Oxygen- containing groups on the surface due to radiation, increased tensile strength up to 50 kGy	Hassan et al. (2013a)
GTR/PP/EPDM	^{60}Co	25, 50, 75, 100	Mechanical tests, TGA, X-ray diffraction (XRD)	Increased tensile strength, modulus and elongation at break; improved thermal properties; crystal structure did not change due to irradiation	Hassan et al. (2014a)
HDPE/recycled HDPE (rHDPE)	Electron beam	165	Mechanical tests, heat deflection temperature (HDT), scanning electron microscopy (SEM)	Increased modulus and tensile strength even at high loadings (60%)	Manas et al. (2018)
HDPE/bagasse	^{60}Co	50, 100, 150, 200, 250	Mechanical tests, TGA, water uptake	Increased tensile strength and modulus up to 100 kGy, improved thermal and water uptake properties	El-Zayat et al. (2019)
LDPE/HDPE	^{60}Co	165	melt flow index (MFI), mechanical tests	Increased MFI with higher loading, tensile strength and modulus increased greatly	Navratil et al. (2015)
LDPE/*sesamum indicum L.*	^{60}Co	25, 75, 125	Mechanical tests, TGA, DMA	Increased tensile and flexural strength along with modulus; improved thermal stability, damping properties deteriorated	Bansal et al. (2023)
LDPE/GTR/feldspar	^{60}Co	50, 75, 100, 150	Mechanical tests, DSC, TGA, electric conductivity, SEM	Increased tensile strength and elongation at break up to 50 kGy, thermal stability improved due to radiation treatment	Hassan et al. (2014b)
Nitrile-butadiene rubber (NBR)/waste rubber ash	^{60}Co	25, 50, 100, 150	Mechanical tests, Soxhlet-extraction, swelling tests, TGA	Sol fraction decreased, while the cross-link density increased; tensile strength greatly increased till 50 kGy	El-Nemr et al. (2017)
Polyethylene terephthalate (PET)/LDPE/EVA	^{60}Co	25, 50, 100, 150	Mechanical tests, DSC, TGA, SEM	Tensile strength greatly increased up to 100 kGy, and up to 10 wt% EVA, elongation at break decreased with dose, but increased with EVA content, thermal stability improved with dose	Abdel et al. (2013)
PET/glass fibre (GF)/epoxy-acrylate	^{60}Co	10	Mechanical tests	Tensile strength and modulus increased due to irradiation; bending and impact strength also improved	Tóth et al. (2004)
Recycled PP/cellulose	EB	5, 50, 100, 250	Tensile tests, TGA, SEM	Tensile strength decreased slightly with increased filler content, but modulus increased due to the irradiation, with the maximum at 10 kGy, thermal stability decreased with the dose	Samat et al. (2018)
PP/PE	^{60}Co	25	Tensile tests, Charpy impact test, DSC, SEM, rheology, electron paramagnetic resonance (EPR)	Improved mechanical and impact properties, also a favorable change in the viscosity	Fel et al. (2016)
HDPE/recycled Polytetrafluoroethylene (PTFE)	EB	50, 100, 150, 200	Gel content, Tensile test, Impact strength, SEM, TGA, DSC, DMA	Gel content increased with the dose (cross-links), increased tensile strength, while the modulus decreased, slight drop in the storage modulus	V et al. (2020)
Recycled LDPE/teak leaves	^{60}Co	75, 125	Tensile- and flexural tests, density, FTIR, SEM, XRD, TGA	Tensile and flexural strength and modulus increased due to the irradiation, thermal stability did not change	Jagdeva et al. (2023)
HDPE/PET/rice husk	^{60}Co	25, 50, 100, 150	Tensile tests, FTIR, TGA, water uptake, SEM	Tensile strength and modulus increased due to irradiation, elongation at break decreased, increased water uptake, thermal stability decreased	Chen et al. (2021)
Styrene-butadiene rubber (SBR)/GTR	^{60}Co	25, 50, 75, 100	Gel content, tensile tests, TGA, hardness, solvent uptake	Gel content increased up to 75 kGy, tensile strength hardness and elongation at break increased with the dose, better thermal resistance	Yasin et al. (2015)
Recycled polyamide (PA)	^{60}Co	100, 350, 500	Rheology, Gel permeation chromatography (GPC), TGA, DSC, EPR, FTIR	Viscosity and molecular weight increased with the absorbed dose (better processability for recycled materials), after 100 kGy the increase was too much, it hindered the processability	González et al. (2023)
PE/GTR/EVA	EB	50, 100, 150, 200	Tensile and impact tests, DMA, cyclic tensile tests, hardness	Increased tensile strength and elongation at break, without a change in the modulus, better energy absorbing properties due to radiation	Mészáros et al. (2012b)

Table 3
Examples of the use of chain scission in polymer recycling.

Materials	Radiation source	Applied doses (kGy)	Test to confirm modification	Attained properties	Reference
Butyl rubber	EB/^{137}Cs	50–500	Soxhlet extraction, molecular weight tests (M_W), Mooney viscosity	Around 100–150 kGy the vulcanized rubber became plasticized, which can be added to a virgin material	Zaharescu et al. (2001)
Butyl rubber	^{60}Co	25, 50, 100, 150,200	Tensile tests, hardness tests	Mechanical properties deteriorated with increasing dose, above 100 kGy, deterioration is greater	Scagliusi et al. (2012a)
HDPE/GTR	^{60}Co	25, 50, 100, 150	Tensile tests, hardness, TGA, FTIR, SEM	Tensile strength, hardness and thermal stability increased with increasing dose, elongation at break decreased	Hassan et al. (2013b)
Isobutylene-isoprene rubber	gamma-radiation	0-200	Viscometric and chromatographic tests	Viscosity and molecular weight decreases sharply with absorbed dose and more at lower dose rates, above 100 kGy, the decrease became more subtle	Şen et al. (2003)
Chlorobutyl rubber	^{60}Co	25, 50, 100, 150 and 200	Tensile tests, TGA	Decrease in the tensile properties at 25 kGy, which became stable after it, thermal stability decreased with the absorbed dose (degradation)	Scagliusi et al. (2012b)
Recycled LDPE/HDPE	^{60}Co	100–2000 kGy	Tensile and impact tests, Soxhlet extraction, FTIR, molecular weight, SEM	Impact energy greatly increased, while elongation at break decreased up to 500 kGy (both became stable above this), tensile strength increased to a small extent	Suarez and Mano (2001)
Recycled PET	EB	30, 50, 70, 100, 300, 500	Viscosity, MW, chemical tests, FTIR, hardness, TGA, water absorption	Both viscosity and molecular weight decreased with increasing dose, better glycolysis yield was observed	Jamdar et al. (2017)
PTFE	EB	0-1000	density, XRD, DSC, tensile tests	Molecular weight and tensile strength decreased with increasing dose (chain scission), while crystallinity increased up to 100 kGy	Oladhosseini and Khorasani (2011)
Waste thermoplastic mix + lignin	EB	n/d	dry distillation, DSC	The EB treatment helped to depolymerize the waste thermoplastic mixture—it can serve as a raw material for green plastics	Chulkov et al. (2019)

gases emitted into the atmosphere from various factories and thus preventing the emission of toxic substances (Mahmoud et al., 2016).

The examples in Table 4 demonstrate that radiation-induced grafting can be used for enhanced recycling of plastic waste by preparing 'compatibilizers', which produce enhanced mechanical performance of products prepared from plastic waste (Czvikovszky and Hargitai, 1997). Both ^{60}Co and electron beam radiation are used here, and good yields can be achieved even at lower doses.

Another use of radiation-induced grafting is to modify plastic waste surfaces to become excellent adsorbents. This is particularly useful, as these materials can capture a variety of toxic substances. In these cases, higher doses (>100 kGy) are required to achieve the desired grafting yield.

4.4. *Functionalization (surface activation)*

As demonstrated before, tailored interfacial adhesion between the phases of a compound can be achieved by radiation-induced grafting. A further approach is based on the functionalization of plastic waste to generate chemically active groups. These groups can enhance wetting and interfacial adhesion and lead to enhanced mechanical performance. These active groups are produced with various chemical treatments, for example with oxidizers like hydrogen peroxide or sulfuric acid. Another less harmful alternative is the radiation-induced functionalization of plastic waste in the presence of air.

During irradiation in air, free radicals are formed on the polymer chains resulting in the formation of various chemically active functional groups such as primary peroxides, hydroperoxides, carbonyl and hydroxyl groups. It is also important to note that some of the oxygen in the air transforms into ozone during radiation treatment, which can also attack the surface of the treated material, and thus activating it. The groups formed in this way can then react with the matrix during processing, improving adhesion in the mixtures (Kiss et al., 2022, 2024; Kiss and Mészáros, 2024).

Table 4
Examples of radiation-induced grafting in plastic waste recycling.

Blend materials	Grafted materials	Grafting procedure	Test to confirm modification	Attained properties	Reference
HDPE/EPDM/GTR	HDPE-g-maleic-anhydride GTR-g-acrylamide	^{60}Co, 10 kGy	DMA, FTIR, Soxhlet extraction, DSC, tensile tests	Tensile strength and elongation at break increased due to compatibilization	Grigoryeva et al. (2008)
HDPE/waste polyurethane	PE-g-MA grafted onto waste PU	EB, 10-70 kGy	Tensile tests, FTIR, SEM, DMA, contact angle, DSC	Tensile strength increased slightly and elongation at break increased greatly with increasing dose, and the storage modulus also increased	Park et al. (2015)
Recycled PET	Vinyl acetate (VAc) grafted onto PET	^{60}Co, 0.2–10 kGy	Tensile tests, FTIR, DMA, TGA	Tensile strength increased up to 3 kGy, while elongation at break had its maximum at 10 kGy, increased thermal stability	Lubna et al. (2018)
Waste PP	PP-g-acrylonitrile PP-g-aminoximated-acrylonitrile	^{60}Co, 2.5–10 kGy, 5.4–6.6 kGy/h dose rate	FTIR, XRD, TGA, SEM, surface area, absorption kinetics	FTIR confirmed successful grafting, the yield increased with the dose and dose rate; adsorption properties increased greatly (Cu ions)	Hassan et al. (2017)
Nylon-6	Nylon-6-g-vinylbenzyl chloride	EB, 25–500 kGy	FTIR, SEM, DSC. XRD, TGA, tensile tests	The degree of grafting increased rapidly up to 300 kGy; suitable for adsorption applications	Ting et al. (2015)
PE/PP fibres	PE/PP-g- N-vinyl-2-pyrrolidone	EB, 25–200 kGy	FTIR, TGA, XPS, iodine adsorption	Degree of grafting had its optimum at 100 kGy; great iodine adsorption (can help remove volatile iodine in nuclear reactors)	Ye et al. (2020)
Poly vinylidene fluoride (PVDF)	PVDF-g-glycidyl methacrylate	^{60}Co, 5 kGy	FTIR, SEM, atomic force microscopy (AFM), porosity, TGA, ion exchange capacity	Degree of grafting was good with the use of radiation; great ammonia adsorption properties (possible bioreactor applications)	Shin et al. (2017)

As a means of reducing the required dose, Kiss et al. (Kiss and Mészáros, 2024; Kiss et al., 2024) carried out radiation-induced functionalization in aerated water. During the radiolysis of water, several strong oxidizers are produced ($OH^{-\bullet}$, H_2O_2), which can attack and activate the surface of the material. This method reduces the required dose for radiation-induced functionalization. Also, during the recycling of rubber, tires are often shredded by water jet grinding, so this method can be easily integrated into the process, as the product in this case is a water suspension.

4.5. Electrical charging (waste sorting)

Plastic waste is often a mixture of several different types of plastics. Thus, it has to be sorted before further processing, as different types of plastics are incompatible with each other. Unfortunately, even a small amount of contaminants can significantly affect the mechanical performance of a product, making the separation of mixed plastic waste an essential step in the recycling process.

The most widespread method for sorting polymer waste in the industry is based on the difference in density. The materials are placed in a series of tanks filled with liquids of varying density, and this way, the different material families are separated. However, the main problem is that roughly 50% of polymer waste is polypropylene and polyethylene, which have very similar densities, which makes it near impossible to separate them effectively with this method. Moreover, they do not blend with each other, so they cannot be processed together. Electron treatment offers a novel approach to solve this problem. When plastic is treated with electrons, it absorbs the negative charges of the primary electrons. The amount and lifetime of these trapped negative electrical charges depend on the temperature, the glass transition temperature and the degree of crystallization of the plastic waste. This way, polyolefins can be separated by electron-assisted electrostatic sorting.

This method has already been successfully applied to separate virgin HDPE, LDPE, and PP, even when they contained various additives (e.g. stabilizers, fillers) and contaminants. The presence of additives and contaminants did not significantly impair the separation of mixed virgin polyolefin. To be suitable for the sorting of mixed polyolefin waste, this method still needs to be tested for mixed recycled plastics with different particle sizes. Reinsch et al. (2014) carried out an experiment using EB assisted electrostatic sorting with LDPE and PP granules. In their work, they were able to separate these two polyolefins with high selectivity, which is an outstanding achievement, as it is a major challenge using other (float-sink separation, infrared spectroscopy etc.) methods.

5. Future prospects

The management of polymer products at the end of their life cycle has been a long-standing issue. Due to its environmental impact, it needs to be resolved. The difficulties begin practically at the collection stage, as most different types of plastic waste are not separated during collection. Product-specific collection systems will help to overcome this issue. Collection is always followed by cleaning and sorting, but a big problem is that a significant of the waste is PE and PP, which are very difficult to separate with traditional methods. Electron treatment is a new approach to this problem—the plastic waste is charged, making the separation of PE and PP possible with high selectivity. The investment cost of low-energy electron accelerators is not very high, therefore they could be integrated into polymer waste sorting processes in the future.

Of course, even after proper sorting, many challenges remain, as the interfacial adhesion in plastic compounds is not adequate. Ionizing radiation offers alternatives to widely used chemical treatments and other technologies. Ionizing radiation may produce covalent bonds between the phases of plastic compounds. It is worth noting that the formation of cross-linked plastics should be avoided, as these are even harder to recycle. Priority should be given to radiation-assisted grafting and surface functionalization, where less material needs to be modified, making the process economically advantageous.

Further examples are high-performance, high molecular weight materials or even cross-linked plastic wastes, which cannot be processed with traditional technologies. Ionizing radiation can reduce the molecular weight of these materials, selectively break down cross-links, or even activate their surfaces after granulation. Also, radiation is safer compared to hazardous chemicals, as it is easy to scale and control.

It is evident, therefore, that ionizing radiation can greatly aid the recycling of polymer waste, helping to achieve a circular economy, which is a key objective of the European Union and the civilization. It allows waste to be reused at the same level or even higher levels (upcycling), and it can be integrated into existing recycling processes. This is supported by numerous research and development efforts, many of which are driven by the IAEA through various CRPs (Coordinated Research Projects) and its NUTEC plastics program, encouraging researchers to explore the potential applications of radiation in polymer recycling. In summary, ionizing radiation could significantly reduce the amount of polymer waste, helping to ensure a far more sustainable future.

CRediT authorship contribution statement

Lóránt Kiss: Writing – original draft, Visualization, Conceptualization. **Uwe Gohs:** Writing – original draft, Visualization, Conceptualization. **Tibor Czvikovszky:** Writing – review & editing, Conceptualization. **László Mészáros:** Writing – review & editing, Visualization, Supervision, Conceptualization.

Declaration of competing interest

The authors have declared no conflict of interest.

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Data availability

Data will be made available on request.

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