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Evaluating Plastic Waste Management in EU Accession Countries: A Life Cycle Perspective from the Republic of Serbia with Microplastic Implications

Dunja Prokić *, Jasna Stepanov, Ljiljana Milošević, Biljana Panin, Nataša Stojić and Mira Pucarević

Faculty of Environmental Protection, Educons University in Sremska Kamenica
* Correspondence: dunja.prokic@educons.edu.rs

Abstract: EU accession countries, including the Republic of Serbia, are under growing pressure to align their plastic waste management systems with EU environmental directives. Despite this, significant challenges remain, including inadequate infrastructure, limited recycling capacity, and weak enforcement mechanisms. This study employs Life Cycle Assessment (LCA) to evaluate the environmental impacts of polyethylene terephthalate (PET) packaging waste in Serbia, focusing on three end-of-life scenarios: landfilling, recycling, and incineration. Using GaBi software and the ReCiPe 2016 methodology, results indicate that mismanaged PET waste contributes notably to terrestrial ecotoxicity (3.69 kg 1,4-DB eq.) and human toxicity (non-cancer) (2.36 kg 1,4-DB eq.). In 2023, 14,967.8 tons of PET were collected by authorized operators; however, unreported quantities likely end up in landfills or the natural environment. Beyond the quantified LCA results, this study highlights microplastic pollution as an emerging environmental concern. It advocates for the development of Serbia-specific characterization factors (CFs) for PET microplastics, incorporating localized fate, exposure, and effect data. Tailored CFs would enhance the precision of impact assessments for Serbian terrestrial ecosystems, contributing to more effective, evidence-based environmental policies. These insights are crucial for supporting Serbia's transition to sustainable waste management and for meeting EU environmental standards

Keywords: plastic; waste; life cycle assessment; polyethylene terephthalate; microplastics

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1. Introduction

Plastic is a synthetic material composed of polymers, which are long, interconnected chains of molecules [1]. Despite its negative aspects, such as low biodegradability and a tendency to absorb harmful toxins, plastic continues to be widely used due to its low production costs and ease of manufacturing, making it a key material in industrial development over recent decades [2]. Global plastic production amounted to 380 million tons in 2022, representing an increase from 353 million tons in 2019, with projections indicating a rise to approximately 590 million tons by 2050 [3]. This continuous rise in plastic production has significantly contributed to the growing levels of plastic pollution in natural environments.

Polyethylene terephthalate (PET) is a widely used plastic, commonly employed in the production of water bottles, food packaging, and textiles. Due to its lightweight, durability, and versatility, PET has become an essential material in modern society [4]. However, waste generated from PET packaging contributes not only to environmental pollution but also poses significant challenges for waste management and disposal [5].

The scale of the plastic waste problem is both significant and rapidly increasing. If current waste management practices persist, the continued rise in plastic production is projected to result in the accumulation of over 9 billion tons of plastic waste in landfills or the natural environment by mid-

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century, with some estimates reaching as high as 17 billion tons [6]. Additionally, by 2050, plastics are expected to account for approximately 15% of the annual greenhouse gas emissions allowance compatible with limiting global warming to below 1.5°C [7].

With the continued increase in plastic production and consumption, it is estimated that 12.0 billion tons of plastic waste will be generated globally by 2050 [8].

Despite the implementation of plastic recycling policies in many countries and regions worldwide—including EU member states—a 2023 report by the United Nations Environment Programme (UNEP) reveals that only 9% of the more than 430 million tons of plastic produced globally each year is recycled [9]. In Europe, less than 30% of total plastic waste is collected for recycling. In recent years, the plastic recycling sector in the EU has faced challenges such as low raw material prices and market uncertainties, while landfilling (31%) and incineration (39%) rates remain relatively high [10]. Although the use of landfills has declined over the past decade, incineration has increased. PET is a fully recyclable plastic that can be reused multiple times; therefore, it should be prioritized for recycling rather than being disposed of in landfills or released into the environment. Recycling is regarded as the most effective and economically viable method for reducing PET waste [11].

The EU has taken a leading role globally by enforcing strict policies and introducing innovative practices to improve recycling rates and support the circular economy [12]. The EU's Circular Economy Action Plan (CEAP) focuses on transitioning from traditional waste management to a more sustainable approach. This includes implementing circular economy principles, promoting renewable energy, improving energy efficiency, and reducing reliance on imported resources. Additionally, it aims to foster economic growth and ensure long-term competitiveness within the European economy [13]. The European Strategy for Plastics in a Circular Economy, adopted in 2018, aims to transform how plastic products are designed, used, produced, and recycled within the EU. The strategy emphasizes that improving the design of plastic products, increasing recycling rates, and producing higher quality recycled materials will help boost the market for recycled plastics. It also supports achieving the UN Sustainable Development Goals, global climate targets, and the EU’s industrial policy objectives [14].

The Republic of Serbia is in the process of accession to the European Union and, as part of this effort, must harmonize its national strategic documents and legislation with EU standards. Serbia has made significant progress in aligning its waste management practices with EU standards In September 2023, the country adopted key legislative measures, including amendments to the Waste Management Law and new regulations governing the handling of specific waste streams [15]. In 2020, Serbia generated over 356.000 tons of plastic waste within its total municipal waste. However, only a small fraction was properly managed—approximately 13% was recycled, 1% was utilized for energy recovery, and about 1.7% was processed through other recovery methods [16]. In 2023, approximately 44,986.4 tons of PET packaging were introduced to the Serbian market. Of this amount, 14,967.8 tons were officially collected by authorized operators within the national packaging waste management system, reflecting the operational efficiency and scope of formal recovery mechanisms for PET waste in the country [17].

Life cycle assessment (LCA) is a methodology that is used to evaluate the environmental impacts of products from the production of raw materials to the products’ end of life [18]. The plastic sector was one of the first adopters of LCA [19,20]. This roadmap outlines and compares key technologies for the treatment of PET waste generated in the Republic of Serbia, using Life Cycle Assessment (LCA) as a decision-support tool. The objective is to identify and promote environmentally and economically viable solutions for managing PET packaging waste.

The analysis focuses on end-of-life treatment options, with the goal of determining best practices that minimize environmental impact and support national waste management targets. Based on LCA findings, this roadmap highlights priority technologies and evaluates their potential for integration into Serbia’s domestic PET waste management system.

2. Challenges in Plastic Waste Management and Environmental Consequences

Plastic waste is accumulating at unprecedented rates, resulting in substantial adverse impacts on environmental systems and human health [21]. A notable example of these impacts is the long-term presence of plastic waste in soil, where it undergoes degradation into microplastics and releases harmful additives such as phthalates [22].

Plastic waste adversely affects ecosystems through multiple pathways. When deposited on land, it contributes to soil pollution, reduces soil fertility, and poses a risk to groundwater quality. It is estimated that approximately 80% of plastic waste ultimately ends up in landfills [10]. Microplastics, in particular, disrupt the natural structure of soil by occupying pore spaces between soil particles, thereby reducing porosity and impeding the movement of air and water—both essential for healthy root development and soil microbial activity. Furthermore, larger plastic fragments can form impermeable layers that hinder water infiltration, further degrading soil quality [1].

A significant environmental concern, particularly in maritime countries, is the disposal of plastic waste into marine environments, leading to widespread pollution of seas and oceans. On a global scale, it is estimated that between 5 and 13 million tons of plastic waste, equivalent to approximately 1.5% to 4% of total annual plastic production, are discharged into the world's oceans each year [10]. Due to limited space and a lack of proper landfill infrastructure, small and underdeveloped countries often resort to incineration or open burning as a means of reducing the mass and volume of plastic waste. However, these practices emit substantial quantities of greenhouse gases (GHGs), carbon oxides (COx), nitrogen oxides (NOx), and various other toxic pollutants into the environment [23].

The issue of inadequately managed or entirely unmanaged municipal solid waste, particularly plastic waste, is especially pronounced in developing countries, where waste management infrastructure and regulatory frameworks are frequently insufficient [24]. These countries and communities face a range of structural challenges in addressing plastic waste, including limited waste collection systems, inadequate financial and institutional capacity to develop, implement, and enforce effective waste management policies, and persistent systemic poverty that often leads to the acceptance of imported plastic waste from other nations [21].

Landfilling, mechanical recycling, and incineration are conventional methods for managing plastic waste [25]. Contemporary landfill systems incorporate advanced engineering measures, such as impermeable bottom liners, to prevent leachate infiltration and control gas emissions (e.g., methane). Nevertheless, in many regions of the world, particularly in developing countries, landfilling continues to pose serious environmental challenges due to inadequate infrastructure and regulatory oversight [14]. Despite these challenges, landfilling offers several advantages over uncontrolled waste disposal. It is a practical and cost-effective approach that does not require the application of complex technologies. Furthermore, it can serve as a source of energy through the generation of methane during the decomposition of plastic waste, and it emits fewer gases compared to plastic incineration [26]. Nevertheless, landfilling has notable drawbacks, especially when waste is deposited in unsanitary conditions, a common issue in many developing regions. During the landfilling process, gases such as methane (CH_4) and carbon dioxide (CO_2) are released, both of which are potent greenhouse gases that significantly contribute to global warming and climate change. Landfills also pose safety hazards due to the potential for explosions and fires. Moreover, leachate generated from landfill sites can contaminate groundwater and soil, while persistent unpleasant odors may degrade the quality of life and reduce property values in surrounding areas [27]. Multiple studies have confirmed that landfills represent a potential source of microplastic release, subsequently facilitating their dissemination throughout various environmental systems. [28] Scientific evidence indicates that the degradation of PET in landfills is extremely slow, with only a small fraction, approximately 1% to 5%, of its carbon content breaking down over 150 years. The remainder may persist for millennia, highlighting the inefficiency and environmental unsustainability of landfilling as a long-term disposal method for PET waste [29].

Plastic waste recycling refers to the process of transforming discarded plastic materials into reusable products through a series of mechanical and chemical operations [26]. Mechanical recycling,

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the predominant method for processing PET waste, encompasses a series of sequential operations, including material collection, classification, size reduction through shredding, decontamination via washing and drying, thermal extrusion into pellets, and further refinement through solid-state polycondensation (SSP) to enhance polymer quality [30]. Despite its widespread use, mechanical recycling faces several limitations, primarily due to polymer degradation that occurs under certain processing conditions. Furthermore, this method is not suitable for heavily contaminated plastic waste and is highly dependent on the effectiveness of sorting operations. As a result of these constraints, only a limited fraction of plastic waste is actually suitable for mechanical recycling [31]. A substantial portion of collected PET bottles is not recycled into new beverage containers, but rather downcycled into lower-quality plastic products with limited or no potential for further recycling [32]. Several scientific studies indicate that plastic recycling facilities may serve as significant point sources of microplastic pollution on a global scale. However, to date, there is no established scientific methodology for quantitatively assessing the generation and environmental release of microplastics during the mechanical recycling of plastic waste at the global level [33].

Incineration is the most extensively studied waste-to-energy (WtE) technology, largely due to its relatively simple and well-established operational procedures [28]. It enables the recovery of energy from waste by converting thermal energy into electrical power, thereby contributing to integrated WtE systems [34]. Various incineration techniques can be distinguished, as this method is applicable to a wide range of waste types beyond just plastics. These include moving grate, fixed grate, rotary kiln, fluidized bed, and specialized incineration methods, such as the burning of combustible materials or thermochemical recycling processes [28]. The negative aspect of plastic waste incineration lies in the release of toxic gases during the combustion process, such as dioxins, furans and polychlorinated biphenyls (PCBs) [23]. Although incineration is widely regarded as a final solution for plastic waste treatment by converting polymers into carbon dioxide and inert mineral residues, studies have shown that residues such as bottom ash may still contain synthetic fibers. This suggests that microplastics and partially combusted plastic fragments can persist post-incineration, posing a risk of secondary environmental contamination through the improper disposal or reuse of incineration by-products [35].

2.1. Overview of Serbia's Plastic Waste Policies

Serbia aims to develop advanced waste management systems that meet the requirements set by the European Union [36]. According to the latest report on Serbia's progress in EU integration, the country is largely aligned with EU legislation in the field of waste management. In September 2023, key regulations were adopted, including amendments to the Law on Waste Management and implementing acts for handling specific waste streams [15]. The key strategic document in this area is the Waste Management Program in the Republic of Serbia for the period 2022–2031, which outlines the strategic objectives for enhancing the national waste management system. It establishes fundamental principles intended to guide all stakeholders in achieving these goals. The program's implementation is expected not only to mitigate environmental and climate-related impacts, but also to create the necessary conditions for integrating waste into the circular economy [37]. The adoption of the Law on Waste Management [38] and the Law on Packaging and Packaging Waste [39] laid the foundation for the establishment and further development of an integrated waste management system in the Republic of Serbia. Additionally, waste management is governed, both directly and indirectly, by a broader set of legal instruments that collectively form the legislative framework for environmental protection and sustainable development in the country.

Currently, there are only 12 sanitary landfills in the Republic of Serbia, which is insufficient to meet the country's waste disposal needs. As existing landfills reach capacity, some municipalities have started redirecting their municipal waste to neighboring regional landfills. The share of the population covered by organized waste collection is steadily increasing, yet the recycling rate remains low. Limited progress has been made in developing sustainable waste management financing mechanisms and in the application of economic instruments. Some landfills that posed environmental risks have been rehabilitated. However, results in the area of hazardous waste management remain inadequate, and the necessary infrastructure for managing hazardous waste has yet to be established [37]. In the Republic of Serbia, over 120 municipal landfills fail to meet environmental standards and accept organized municipal waste. Additionally, more than 3,500 illegal dumpsites exist, beyond the control of municipal utilities, posing significant environmental risks. Approximately 20% of municipal waste is disposed of in these unauthorized sites [17].

According to data from the Serbian Environmental Protection Agency (SEPA) for 2023, eight operators are licensed for packaging waste management. In 2023, the quantity of plastic packaging placed on the market in the Republic of Serbia by legal entities or entrepreneurs who transferred their obligations to licensed operators amounted to 96,483.9 tons. Out of the total quantity of plastic packaging, 44.986,4 tons were composed of PET, while the remaining volume consisted of other plastic polymers. Out of this amount, a total of 14.967,8 tons of PET waste was recovered for reuse [49]. A particular challenge in the Republic of Serbia is the inadequate establishment of a system for the separate collection of households packaging waste, resulting in the majority of plastic waste being disposed of as part of mixed municipal waste. This significantly hinders its potential for further utilization and recycling [37]. Additionally, there is currently no dedicated legal or regulatory framework in Serbia that addresses microplastics within waste streams. The absence of specific policies and guidelines for the monitoring, control, and management of microplastics highlights a critical regulatory gap, especially given their increasing presence in the environment and potential risks to human health and ecosystems.

3. Literature Review: LCA in Plastic Waste Reduction Strategies

Life cycle assessment (LCA) is a methodology that is used to evaluate the environmental impacts of products from the production of raw materials to the products' end of life [40]. Life cycle analyses flows were initially determined for the depletion of material and energy resources [41]. Life cycle assessment can be successfully used to analyze the environmental impact of different stages of a product's life cycle [42]. It is possible to devise environmental impact reduction solutions at different life cycle stages, because of the variety of developed databases and software programs [43]. Life cycle assessment (LCA) is a method to calculate the potential environmental impacts of products from a supply-chain perspective, i.e. by accounting for the impacts associated with the emissions and resource consumption taking place throughout the whole life cycle of a product, from raw material acquisition and pre-processing through product manufacturing, distribution, use and waste management of the product at end of life [44].

The plastic sector was among the first to adopt Life Cycle Assessment (LCA) as a tool for evaluating environmental impacts [45,46]. Assessing the life cycle of plastic products is essential for promoting sustainability. Practical strategies for advancing a circular economy often focus on extending product life cycles, thereby reducing resource consumption and minimizing waste generation [47].

The main composition of microplastic particles varies based on the polymer type from which they are derived, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET) [46]. The potential toxicity of microplastics are not only linked to the composition of the original plastic materials, but also to their inherent physicochemical characteristics, which allow them to act as a vector that facilitates the transfer of toxic compounds from the environment into organisms [48]. One of the biggest obstacles in mitigating microplastic pollution as well as understanding their fate and transport in/between environmental compartments is the plurality of both primary and secondary sources of microplastics [46]. The release of toxic monomers and oligomers within organisms is a major concern [49]. But attention must also be paid to the endocrine-disrupting additives that are added to the raw polymers during manufacturing [46]. Manufacturing stage must be considered in order to develop innovative technologies based on life cycle assessments. At the production stage, it is important to consider that plastic waste can be treated via disposal, incineration, or recycling processes [50].

LCA provide understanding of the environmental performance of the plastic industry by taking into considerations five life-cycle phases, including material extraction (cradle), manufacturing (gate), use (customer), distribution/transportation and end-of-life (grave). All phases can be analzsed or selected elements of the value chain can be studied [46].

Life cycle analysis with looping method in the production stage promotes sustainable production by maintaining the value of products [51]. In the production phase, the use of renewable raw materials has increased in recent years and waste generation has decreased [52].

The use of life cycle assessment at early planning stages gives neither final nor accurate results but can have a great impact on the environmental performance, especially when comparing scenarios [53].

The specific requirements for LCA were documented by The International Organization for Standardization (ISO) in standards 14040:2006 and 14044:2006. An LCA has four stages, including (i) goal and scope definition; (ii) life-cycle inventory analysis (LCI); (iii) life-cycle impact assessment (LCIA); and (iv) interpretation. The first stage describes the intended application, system boundaries and the functional unit of the study. The LCI stage involves the collection and verification of input/output and emission data. The LCIA stage transform these data into meaningful metrics, such as global warming potential (commonly expressed as "kg CO_2-eq"). The interpretation phase contextualises these metrics into recommendations and discusses the possible limitations of the LCA model. These four steps may be iteratively revised to progressively improve the model if there are more information [46,54].

4. Materials and Methods

4.1. Study Area

This study investigates the environmental impacts of PET packaging waste management in the Republic of Serbia, using data from 2023 reported by the Serbian Environmental Protection Agency (SEPA). In that year, 14,967.8 tons of PET packaging waste were generated, forming the basis for the life cycle assessment (LCA) conducted in this research.

4.2. LCA Modeling Approach

The Life Cycle Assessment was performed using GaBi software (Sphera Solutions GmbH, Germany) to model and compare three waste management scenarios specific to PET packaging waste in Serbia: landfilling, mechanical recycling, and incineration. The system boundaries were set to include processes from the point at which PET packaging waste enters end-of-life treatment (i.e., post-consumer phase) through to final disposal or material recovery. The functional unit for the analysis is defined as 1 ton of PET packaging waste.

GaBi was selected due to its robustness, access to verified databases (e.g., Ecoinvent, CML2001), and its flexibility in modifying process flows and background data. The software allowed for high-resolution modeling of material and energy flows, emissions, and environmental impacts relevant to the Serbian context.

4.3. Waste Management Scenarios

The three selected treatment scenarios—landfilling, recycling, and incineration—were developed to reflect typical waste handling practices observed in Serbia. While waste generation, collection, and transport stages remain constant across scenarios, the final treatment method varies and serves as the basis for comparative analysis.

Landfilling was modeled as disposal in non-sanitary landfill conditions, which are still common in parts of Serbia.

Mechanical recycling considered the typical PET bottle recycling process, including sorting, shredding, washing, extrusion, and pelletizing.

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Incineration was modeled as waste-to-energy combustion, based on typical European operational parameters.

4.4. *Impact Categories and Evaluation*

The environmental evaluation focused on selected midpoint impact categories relevant to the study's objectives and the limitations of Serbia's current waste infrastructure. The categories analyzed were: climate change, human toxicity, and terrestrial ecotoxicity.

These were chosen due to their strong association with plastic waste treatment processes and their policy relevance, particularly concerning the environmental performance of different PET end-of-life strategies.

4.5. *LCA Methodology*

Life Cycle Assessment (LCA), as defined by ISO 14040 [54], is a systematic approach to quantify the environmental impacts associated with a product or service throughout its entire life cycle. This study applies the LCA methodology to evaluate the environmental performance of different end-of-life management options for PET packaging waste in the Republic of Serbia.

Following the ISO 14040 framework, the study was conducted in four phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.

4.5.1. Goal and Scope Definition

The primary goal of this study is to quantify and compare the environmental impacts of three PET waste management scenarios—mechanical recycling, landfilling, and incineration—in order to identify the most environmentally sustainable option for Serbia. The system boundary is defined from the point at which PET packaging waste enters end-of-life treatment. The functional unit used for comparison is one metric ton (1 t) of PET packaging waste. The study is based on PET waste data from Serbia, where 14,967.8 tons of PET packaging waste were collected in 2023.

4.5.2. Life Cycle Inventory (LCI)

The inventory phase involved collecting data on inputs, outputs, and emissions related to the three waste treatment processes. These data were modeled using GaBi LCA software, incorporating unit processes for PET landfilling, recycling, and incineration. Waste generation and treatment data were sourced from the Serbian Environmental Protection Agency (SEPA) and relevant literature to ensure accuracy and representativeness for the Serbian context.

4.5.3. Life Cycle Impact Assessment (LCIA)

The environmental impacts of the PET waste treatment scenarios were assessed using the ReCiPe method integrated within GaBi software. This method provides midpoint impact indicators, such as greenhouse gas emissions, and endpoint indicators covering damage to human health, ecosystems, and resource depletion. The study focused on key impact categories relevant to PET waste management, including global warming potential and ecotoxicity, to capture the most critical environmental effects associated with each scenario.

4.5.4. Interpretation

The interpretation phase involved comparing the environmental impacts of recycling, landfilling, and incineration of PET waste in Serbia. The results highlight the advantages and disadvantages of each treatment option, with particular attention to impacts related to global warming and ecotoxicity, which are significant due to the predominance of landfill disposal in Serbia. The findings provide evidence-based recommendations to inform the development of more sustainable PET waste management strategies aligned with Serbia's environmental goals.

5. Results and Discussion

This study evaluated the environmental impacts of three end-of-life (EoL) treatment scenarios for 14,967.8 tons of PET packaging waste—landfilling, recycling, and incineration—across four impact categories: Climate Change, Human Toxicity, and Terrestrial Ecotoxicity. The results clearly demonstrate that the environmental burden varies significantly depending on the waste management strategy implemented (Table 1).

Table 1. Environmental impacts of end-of-life treatment for 14,967.8 tons of PET packaging, derived using GaBi software.

Midpoint	Unit	Landfill	Recycling	Incineration
Climate Change/Global Warming	kg CO2 eq.	451,000	-24,500,000	34,400,000
Human Toxicity, cancer	kg 1,4-DB eq.	16,900	-342,000	1,720
Human Toxicity, non-cancer	kg 1,4-DB eq.	35,400	-3,720,000	2,210
Terrestrial ecotoxicity	kg 1,4-DB eq.	55,300	-5,960,000	54,600

Among the three scenarios, recycling emerges as the most environmentally favorable option across all assessed categories. It is associated with negative values in every impact category, indicating environmental benefits through avoided emissions and resource conservation. Specifically, recycling results in a net reduction of 24.5 million kg CO_2 eq., highlighting its substantial mitigation potential for climate change. Likewise, the process contributes to a significant decrease in toxicity indicators, including a reduction of 342,000 kg 1,4-DB eq. in human toxicity and 5.96 million kg 1,4-DB eq. in terrestrial ecotoxicity.

Given these results, further analysis focuses on comparing landfilling and incineration, which represent less sustainable practices. Landfilling was identified as the least favorable option in two of the four impact categories—Human Toxicity and Terrestrial Ecotoxicity—due to high emissions to soil, which lead to long-term environmental degradation. Conversely, incineration had the highest impact on climate change, emitting approximately 34.4 million kg CO_2 eq. This outcome underscores the significant air pollution burden associated with the combustion of PET, particularly in terms of carbon dioxide emissions.

The midpoint characterization results for the environmental impacts of 1 kg of PET waste in the Republic of Serbia indicate that the most significant contributions are observed in terrestrial ecotoxicity, with emissions of 3.69 kg 1,4-dichlorobenzene equivalents (1,4-DB eq.) resulting from landfill disposal, and in climate change, with 2.29 kg CO_2 equivalents emitted due to incineration. These figures affirm the distinct environmental profiles of the two EoL scenarios: landfilling has more severe implications for soil ecosystems, while incineration poses a greater threat to atmospheric stability and human health via air emissions.

In addition to the modeled impact categories, it is essential to consider the emerging issue of microplastic pollution, which is not yet fully captured in standard life cycle assessment (LCA) methods. Both landfilling and incineration of plastic waste contribute to the formation and release of microplastics—landfills through physical degradation over time and leaching into soil and water, and incinerators via incomplete combustion or release of fine particulate residues. These microplastics represent a long-term and poorly understood risk to ecosystems and human health, indicating the need for expanded impact categories and new characterization models within LCA frameworks.

Determining the best EoL treatment option for PET waste requires more complex analyses that include multiple impact categories, normalization, weighting, and sometimes even endpoint

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modeling. However, even with such detailed analyses, there may not be a universally "best" option, but rather one that is more or less suitable depending on the priority impact categories or local environmental context.

Therefore, the LCA method should be regarded primarily as a supporting tool for decision-makers, helping to identify environmental hot spots and trade-offs rather than providing absolute answers. Future enhancements to LCA, particularly the integration of emerging impact pathways such as microplastic pollution, will be crucial for better evaluating the full spectrum of environmental consequences associated with plastic waste management.

6. Challenges and Opportunities in Applying LCA to Microplastics

Landfills represent a significant but often overlooked source of microplastic pollution in terrestrial ecosystems. One of the key pathways for microplastic release into soils is through untreated landfill waste, which undergoes physical and chemical degradation over time. Microplastics have been detected in landfill leachate across several Chinese cities, with concentrations ranging from 0.420 to 24.6 particles per liter. The dominant polymer types identified were polypropylene (PP) and polyethylene (PE), reflecting the widespread use of these plastics in consumer packaging. [55]

The challenge is expected to intensify in the coming decades. With the global demand for plastics continuing to rise, it is estimated that approximately 12 billion tons of plastic waste will be generated worldwide by 2050 [8]. When plastic waste is disposed of in landfills, it can persist in the soil environment for extended periods. Through processes such as UV radiation, mechanical abrasion, and chemical weathering, these materials gradually fragment into microplastics, which may also leach toxic additives, including phthalates and other hazardous chemicals [22]. These substances pose potential risks to soil health, groundwater quality, and ultimately, human and ecological health.

Microplastics have been detected in both leachate and solid waste from landfill sites. For example, concentrations in leachate and garbage from a Shanghai landfill reached 8.00 ± 3.00 particles/L and 62.0 ± 23.0 particles/g, respectively [56]. The heterogeneous composition of landfill environments, characterized by high organic matter content, complicates pollutant removal. Conventional pretreatment methods are often insufficient, and extended digestion times or the application of strong acid or alkaline solutions may be required to reduce organic interference. However, subsequent microscopic analysis and classification of microplastics are necessary to improve detection accuracy. Current studies primarily focus on larger microplastics, with limited data available for particles at the micrometer (μm) and nanometer (nm) scales.

Microplastic and heavy metal contamination has also been investigated in fly ash, bottom ash, and surface soil from municipal solid waste incineration (MSWI) facilities. The abundance of microplastics was reported as 23, 171, and 86 particles/kg dry weight in fly ash, bottom ash, and soil samples, respectively. The dominant microplastic type in fly ash was fiber, while fragments were most prevalent in bottom ash (43.0%) and soil (29.3%), followed by films, foams, and fibers in varying proportions. Many particles exhibited physical degradation features such as tearing marks, protrusions, and surface scratches.

Notably, microplastics were found to adsorb heavy metals including Cr, Cu, Zn, and Pb, indicating a potential vector for pollutant transport. Column leaching experiments demonstrated that both microplastics and heavy metals could be mobilized from bottom ash under simulated precipitation. In particular, acid rain significantly enhanced the leaching of heavy metals into the aqueous phase in the absence of appropriate containment or treatment measures. These findings highlight the potential for combined migration of microplastics and heavy metals from incineration residues and emphasize the need for improved management strategies.

While incineration significantly reduces the volume of municipal solid waste destined for landfilling, it does not eliminate the need for landfill disposal. Incineration produces bottom ash, a residual material that is often returned to the environment. It is generally regarded as an effective method for the destruction of plastic waste, converting polymers primarily into CO_2 and inert mineral fractions [8]. However, studies have shown that unburned materials, including synthetic fibers, can persist in bottom ash, suggesting that microplastics (MPs) may survive the combustion process and potentially enter the environment through the reuse or improper disposal of incineration residues [57].

To investigate whether incineration fully eliminates MPs and to quantify their presence in bottom ash, recent research has focused on extracting and characterizing MPs from this waste stream. Findings revealed that bottom ash is a previously overlooked source of microplastics, with reported abundances ranging from 1.9 to 565 particles/kg, corresponding to an estimated 360 to 102,000 microplastic particles per metric ton of incinerated waste. These results highlight the need for further studies on the fate and environmental risks of microplastics in incineration residues.

7. Future Research Directions on PET Microplastic in Serbia

Recent developments in Life Cycle Assessment (LCA) increasingly address the environmental impacts of microplastics, with a predominant focus on aquatic ecosystems and various polymer types. Notably, several studies have contributed to advancing LCA methodologies by developing characterization factors (CFs) that quantify the physical and ecotoxicological impacts of microplastic emissions. One such study addresses a critical gap by formulating CFs for microplastics in aquatic environments. Building on the efforts of the MarILCA working group—initiated in 2018 with support from the UN Environment Life Cycle Initiative and the Forum for Sustainability through Life Cycle Innovation (FSLCI)—the study updated exposure and effect factors (EEFs) using recent ecotoxicity data and developed fate factors (FFs) for 11 common polymers, incorporating a range of particle shapes and sizes. The findings emphasize the influence of polymer density and particle size on environmental behavior in aquatic systems. By integrating these parameters, midpoint and endpoint CFs were generated to assess ecosystem damage, with associated uncertainty quantified through Monte Carlo simulations. Case studies involving food packaging illustrated the applicability of these CFs in improving LCA outcomes by accounting for the previously overlooked impacts of microplastics on aquatic biota. Additionally, default CFs based on polymer density classifications (low, medium, high) and particle morphology (e.g., spheres, fibers, films) were introduced to support practitioners in scenarios lacking detailed emission data [58].

Complementary research has also focused on biodegradable polymers in marine environments, seeking to fill gaps in accounting for their ecological impacts. Degradation rates for poly(lactic acid), poly(butylene succinate), and poly(ε-caprolactam) were experimentally determined over six months in natural seawater, incorporating variables such as particle size, polymer grade, and temperature. These data informed fate modeling by including key environmental processes such as sedimentation, resuspension, and burial, leading to the development of polymer-specific CFs. When applied to the life cycle of a synthetic sports shirt made from biodegradable fibers, microplastic emissions were found to contribute up to 30% of the total impact on ecosystem quality. This work strengthens the LCA framework by introducing empirically derived CFs that support more informed material selection and environmental assessments [59].

A further advancement involved the development of CFs for aquatic microplastic pollution from polymers such as polypropylene (PP), low-density polyethylene (LDPE), and polyethylene terephthalate (PET). Utilizing the multimedia fate model Simplebox4Plastics, the study modeled environmental fate and assessed ecological effects using species sensitivity distributions. Macroplastic impacts were incorporated using a conversion factor. The resulting CFs were integrated into the ReCiPe2016 life cycle impact assessment (LCIA) method and applied to consumer packaging scenarios. The results revealed a significant contribution of plastic pollution to freshwater and marine ecotoxicity categories, although its effect on endpoint ecosystem quality was comparatively limited. These findings underscore the necessity of integrating plastic-related impacts into mainstream LCIA methods and highlight the need for continued refinement across a broader spectrum of polymer types and fate-effect modeling approaches [60].

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With respect to terrestrial ecosystems, CFs have been developed to evaluate the impacts of both fossil- and bio-based plastics, particularly regarding microplastic ingestion and the release of chemical additives. This work assessed polymers such as PP, LDPE, and biopolymers including polyhydroxyalkanoates (PHA) and PLA. Fate factors were derived from photooxidative degradation data under terrestrial conditions, while effect factors followed USEtox guidelines and incorporated both ecotoxicological and physical impact data. Under the assumption of full bioavailability (exposure factor XF = 1), chemical additives were found to pose substantially higher environmental risks than microplastic ingestion—by up to three to four orders of magnitude—especially in aquatic ecosystems. Importantly, the CFs developed for biopolymers were comparable to those for conventional plastics, indicating that improved waste management strategies are essential for both material types across terrestrial and aquatic environments [61].

Building on these foundational studies, future research in Serbia should focus on developing region-specific characterization factors (CFs) for mismanaged PET plastics in the terrestrial environment, taking into account both the physical impacts of microplastic ingestion and the ecotoxicological effects of their additives. This involves tailoring existing LCA methodologies to the unique environmental conditions, soil characteristics, and waste management practices of Serbia.

A primary objective is to establish the fate factor (FF) for PET plastics in Serbian soils through a combination of laboratory testing and in-situ environmental insights. To ensure accurate modeling, the fate assessment should also incorporate local waste management practices, estimated plastic leakage from various sources, the extrinsic and intrinsic properties of plastics, and relevant environmental conditions drawn from national and scientific reports. This integrated approach will support a realistic representation of the dispersion and persistence of PET plastics and their microplastics in terrestrial compartments. [58,61,62].

For the exposure factor (XF), initial assumptions may consider full bioavailability (XF = 1), but detailed investigation of soil physicochemical properties such as organic matter content, pH, and moisture will enable refined bioavailability estimates. These data can be sourced from Serbian soil databases and targeted field sampling [61].

The effect factor (EF) should be derived from ecotoxicological data on local terrestrial species, whose sensitivities may differ from those reported in global studies. Chronic toxicity endpoints (e.g., EC10, NOEC, EC50) for soil invertebrates, plants, and microorganisms native to Serbia should be gathered through laboratory assays and literature reviews. Additionally, environmental monitoring data on PET-associated additives in Serbian soils would facilitate assessment of chemical risks [60,61].

By integrating these localized fate, exposure, and effect factors, standardized CFs can be developed to quantify the impacts of PET plastics and microplastics on Serbian terrestrial ecosystems. Such advancements will enhance the precision of LCIA models in Serbia and provide evidence-based support for environmental policymaking and waste management strategies tailored to the country's specific challenges with plastic pollution [58–62].

8. Conclusions

This study represents the first application of GaBi software to assess the environmental impacts of PET waste management in Serbia, an EU accession country. The results demonstrate that recycling is the most environmentally beneficial option, leading to substantial reductions in climate change potential, human toxicity, and terrestrial ecotoxicity. In contrast, landfilling and incineration significantly contribute to environmental degradation, particularly through emissions and the long-term accumulation of pollutants.

Despite data uncertainties and the sensitivity of the results, the findings offer a comprehensive overview of the current baseline scenario for PET waste management in Serbia. They also highlight critical shortcomings in existing waste management practices and identify opportunities to reduce environmental impacts. Furthermore, this research contributes to the growing—yet still limited—collection of LCA studies on plastic waste in regions with similar geographical and socio-economic conditions.

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Finally, this paper lays the groundwork for future research in Serbia aimed at developing region-specific characterization factors (CFs) for microplastics originating from mismanaged PET in terrestrial environments, through close collaboration between experimental research and LCA modeling.

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