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Review article

Resource or waste? A perspective of plastics degradation in soil with a focus on end-of-life options. One step beyond

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A R T I C L E I N F O

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A B S T R A C T

Plastics have surpassed traditional materials across numerous industries due to their versatility, durability, and cost-effectiveness. However, their persistence in ecosystems, particularly in soil, presents serious environmental challenges. This narrative review builds on previous work by analysing over 300 studies on plastics in soil, with a focus on degradation and potential reuse. Special attention is given to research published since 2019. The review classifies plastics by resin type and examines their degradation processes under various soil conditions, covering both conventional and biodegradable polymers. Polyethylene emerges as the most extensively studied polymer, while interest in biodegradable alternatives like polylactic acid (PLA) and polybutylene adipate-co-terephthalate (PBAT) is increasing. Additionally, the review highlights advancements in microplastics research, particularly their interactions with co-contaminants and effects on soil organisms. Despite significant progress, challenges remain in standardizing methods for measuring plastic degradation in soil. The review emphasizes the need for further research to establish consistent methods and reliable indicators for degradation, while also exploring innovative recycling technologies for use in agricultural soil management. It stresses the importance of advancing a circular economy for plastics, integrating policy and practical solutions to reduce environmental impacts.

1. Introduction

The Heliyon journal, launched in 2015, is celebrating its 10th anniversary with a special issue titled "Heliyon 10th Anniversary Special Issue." I was invited to contribute by writing a follow-up study based on a previous work published in Heliyon [1], highlighting how the issue has evolved over time. Therefore, this paper serves as a follow-up to that earlier reflections. The original studies on

Abbreviations: ***ABS***, acrylonitrile-butadiene styrene; ***BIO***, biodegradable mulch film; ***BPA***, bisphenol A; ***CHI***, chitosan; ***DBP***, dibutyl phthalate; ***DEHP***, di-(2-ethylhexyl) phthalate; ***DINP***, diisononyl phthalate; ***DMAc***, dimethylacetamide; ***DMP***, dimethyl phthalate; ***ECHA***, European Chemicals Agency; ***EEA***, European Environment Agency; ***EPR***, extended producers responsibility; **EPS**, expanded polystyrene; ***EPDM***, ethylene-propylene-diene-monomer; ***EVA***, ethyl vinyl acetate; ***LDPE***, low-density polyethylene; ***NOAA***, National Oceanic and Atmospheric Administration; ***PA***, polyamide; ***PAEs***, phthalate acid esters; ***PAM***, polyacrylamides; ***PBAT***, polybutylene adipate-co-terephthalate; ***PBS***, polybutylene succinate; ***PBSA***, polybutylene succinate-co-adipate; ***PCL***, polycaprolactone; ***PC***, polycarbonate; **PCB**, polychlorinated biphenyl; ***PDA***, polydopamine; ***PE***, polyethylene; ***PET***, polyethylene terephthalate; ***PHA***, polyhydroxyalkanoates; ***P3HB***, poly3-hydroxybutyrate; ***PHU***, polyhydroxyurethane; ***PLA***, polylactic acid; ***PMMA***, polymethylmethacrylate; ***PP***, polypropylene; ***PS***, polystyrene; ***PVA***, polyvinyl alcohol; ***PVC***, polyvinyl chloride; ***UNEP***, United Nations Environment Programme; ***UVA***, ultraviolet absorbers.

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plastics (Table S1) examined the dual nature of plastics in soil management. It explored the benefits and challenges of using plastics, for instance in agriculture, particularly the degradation process of plastics in soil and the various end-of-life options for these materials (Fig. 1). They highlighted the role of plastics as both a valuable resource for enhancing agricultural productivity and as a potential environmental hazard due to the challenges associated with their degradation and disposal. These studies aimed to provide a balanced perspective on whether plastics should be viewed primarily as a resource or as waste, highlighting the importance of sustainable end-of-life strategies for plastic materials. In the past decade, research primarily concentrated on the benefits of plastic use in soil management, with particular focus on plastic mulching and the mechanical properties of soils. Earlier studies highlighted the positive effects of plastic mulches on crop productivity, such as increased yields resulting from improved moisture and temperature regulation. The emphasis was largely on these immediate agronomic advantages, although concerns about the long-term impacts of plastic use, especially soil degradation, were beginning to surface [2–6]. In the past five years, there has been a clear shift in focus towards examining the environmental impacts of plastics in soil, with growing attention on microplastics. Researchers have begun to explore how plastics degrade in soil environments and the resulting effects on soil health and related ecosystem services. The role of biota in the transport of microplastics has also emerged as a new area of interest [7–10]). Emerging areas of research include the effects of microplastics on soil biota, the biodegradability of plastics, and the development of alternative materials. There is growing interest in modeling the movement and fate of microplastics within soil. Specific topics of focus include analytical methods for detecting microplastics in soil [11], the impact on soil microbial communities [12,13], effects on soil environments and carbon cycling [14,15], as well as the origin, quality [10,16,17], and movement of these particles [18]). There is also a growing body of research focused on the implications of plastic use in agriculture from a management perspective, practical applications and policy development [19–25].

This focus on key areas that reflect the latest developments in the field. These include the impacts of microplastics on soil health, with attention to their long-term effects and the models predicting their movement, distribution, and fate within soil. The review also examines the biodegradability of different plastics, the potential of alternative materials—assessing their degradation in soil—and explores changes in microbial diversity and function, as well as their role in soil processes. In addition, it addresses management practices and policy development concerning plastic use, particularly in agriculture.

2. Plastic degradation, microplastics, and recycling

2.1. New findings on plastic degradation in soil

Factors such as soil type, temperature, and the presence of specific microorganisms significantly influence the degradation rates of both conventional and biodegradable plastics. Zumstein et al. [26] found that soil composition significantly influences the microbial

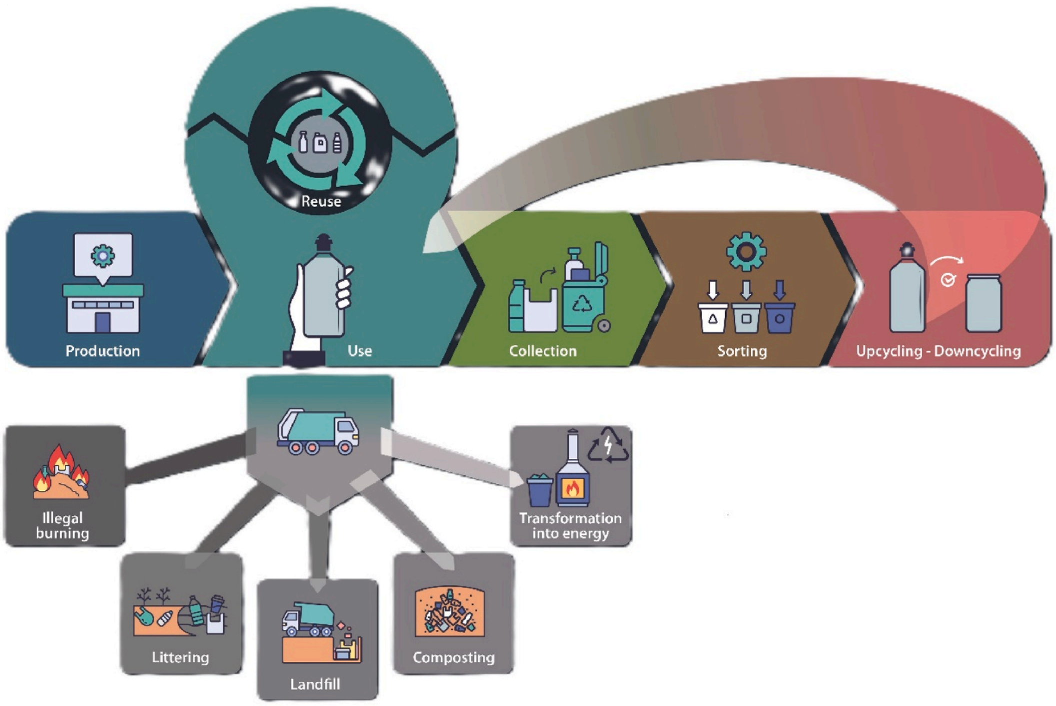

Fig. 1. The life cycle of a plastic item, from production to recycling. This review discusses and enriches research in the field of plastics management by compiling current knowledge on plastic disposal and management from an environmental perspective, with a focus on degradation processes [©Elsevier].

community structure, which in turn affects the physical interactions with plastic particles and their degradation process. Pischedda et al. [27] and Dong et al. [28] highlighted that temperature has a significant impact on the biodegradation rate of plastics, with higher temperatures generally enhancing microbial activity, thus accelerating the breakdown of plastics. Zhang et al. [8] identified the presence of certain microorganisms, such as specific bacteria and fungi, as key determinants in the efficient degradation of plastics. These organisms produce enzymes capable of breaking down polymer chains. Tiwari et al. [29] found that specific microorganisms, such as *BreviBacillus brevis*, are effective in breaking down polyethylene microplastics in soil through enzymatic action. While Janczak et al. [30] explored the impact of soil type on the biodegradation of polylactic acid (PLA) and polyethylene terephthalate (PET) polymers, noting that different soil compositions support varying microbial communities, which in turn affect degradation rates. If compared, paper mulch degraded almost completely in soil within 12 months while PLA and polybutylene adipate-co-terephthalate (PBAT) do not degrade as effectively in soil, although they perform quite well in compost [31]. But, it is not only plastics, per se, that impact the soil, but also molecules that can be released during degradation [32].

Expanded polystyrene (EPS) is one of the most significant plastic polymers due to its low density, which causes it to occupy a large volume when it becomes waste, making even temporary storage difficult [21]. Insects are among the most promising organisms for degrading this material [33]. For instance, insects such as *Plodia interpunctella* (Indian meal moth larvae), yellow mealworms (*Tenebrio molitor* larvae), and *Uloma* species are among the most promising organisms for plastic degradation [34–36]. These insects consume plastics like PE and PS, while bacteria in their digestive systems—such as *Enterobacter asburiae*, *Bacillus*, and *Pseudomonas*—help break down the polymers into smaller molecules. These processes are facilitated by the insect's gut enzymes and microbial bioactivity.

2.2. The expanding scope and environmental impact of microplastics research

Research on microplastics (Fig. 2) has experienced a rapid surge in publications in recent years. From 2021, the number of publications has increased significantly, the research community is paying particular attention to soil contamination and the interactions of microplastics with environmental and biological systems. These trends indicate that the field of microplastics research is not only expanding in volume but also diversifying in scope, with a significant focus on environmental impacts, especially related to soil. As of 2021, the cumulative total of 1599 papers and 28,017 citations (WoS, Clarivate) demonstrates the field's growth, though the increasing volume of research may make it challenging to identify the most useful studies in the future. This extensive body of research has made it clear that microplastics are now ubiquitous, easily transported across distances and capable of penetrating organisms. Their global presence, even in remote regions, has been confirmed by findings in Antarctic snow, showing that these particles can travel long distances [37]. It is now known, quantified, that some polymers produce more microplastics than others as they age in the soil [38]. The ingestion of microplastics by animals and their incorporation into plants raise concerns about their potential transfer through the food chain [39–41]. Indeed, microplastics have already been detected in human tissues [42–45], with the potential for worse outcomes if microplastic contamination is combined with other pollutants [46]. Advancements in research have also made it

Fig. 2. Microplastics are plastic particles smaller than 5 mm, arising from various sources, such as the breakdown of larger plastic debris or intentional production for industrial uses. This definition, derived from organizations like UNEP, NOAA, ECHA, and EEA, covers a broad range of plastics, including primary microplastics (manufactured to be small) and secondary microplastics (formed by the degradation of larger items). An analysis of multiple studies on microplastics in various soils, across different land uses and global regions [17], revealed the following qualitative-quantitative traits: median quantity 112 particles kg^{-1} (Q1: 12 particles kg^{-1}, Q3: 863 particles kg^{-1}), median size 305 μm (Q1: 50 μm, Q3: 862 μm), and median quality PE, PP, PS (secondary polymers include PET, PVC, PA, PU, ABS). (DALL·E image).

easier to detect even the smallest microplastics, using non-invasive techniques. Scheurer and Bigalke [47] were among the pioneers in publishing a protocol for microplastic analysis in soils, enabling the assessment of particle size and quantity using μ-FTIR analysis. Subsequent researchers have proposed alternative methods [48–50], which, while effective in the laboratory, prove to be quite challenging in practical applications. Developments in detection methods, such as laser direct infrared spectroscopy [45] and hyperspectral stimulated Raman scattering imaging [51], now allow for the identification and characterization of microplastics at the single-particle level, even in complex environments and biological samples.

What is certain is that microplastics were originally macroplastics before reaching the smaller size that classifies them as such. While quantifying them in space is challenging, it provides a valuable foundation for both future research and management efforts [52].

2.3. Advances in recycling technologies or practices

In terms of reuse, the possibilities studied are numerous in the case of engineering uses, in particular soil stabilization [53–55].

For over a decade, the industry has shown a strong interest in plastic polymer substitutes, especially in light of potential bans on single-use plastic items. This has spurred research into these alternatives [26,28,56]. Additionally, studies have explored pre-treatment techniques like bioaugmentation [57] and investigated the environmental fate and impacts of these materials [58], others focused on conversion of waste plastics into value-added aromatics [59] or, at least, generating energy [60].

Recent advancements in recycling technologies have significantly improved the management of plastic waste. The initial challenge lies in identifying plastic within soil matrices, but new methods, such as density separation and electrostatic techniques, have enhanced the precision in detecting and quantifying microplastics [49,61,62].

There are also innovative proposals for repurposing PET bottles, such as filling them with soil to create walkways or even support heavier loads [63]. While this approach has shown promise on an experimental scale, the idea of using soil-filled bottles to prepare the subfloor of a supermarket car park appears impractical in reality.

2.3.1. Lessons learned from space mission planners

Out of Earth, managing space waste, particularly reducing the final volume of end-of-life (EoL) materials, is crucial. Future human missions will likely be more constrained by mass than volume but maximizing the net habitable volume for the crew remains a key objective. This approach parallels strategies for managing waste on an increasingly crowded Earth. In space, waste is compressed, wrapped, and stored to minimize space [1]. Previous experience on the NASA shuttle and ISS showed that liquids could still leak, leading to the use of Heat Melt Compactor which compresses waste, especially those containing plastics, into stable disposal objects.

Fig. 3. For long-term missions, astronauts need facilities for living, working, transportation, communication with Earth, and producing essential resources like oxygen and water. Transporting all this infrastructure from Earth would be extremely costly. To address this, the European Space Agency is exploring the possibility of 3D printing some of these facilities on Mars using the planet's soil. They are also exploring ways to recycle waste, such as repurposing unused plastic packaging, into new materials (Photo: FOTEC/©ESA).

Reducing volume and creating recyclable items is an existing strategy in space and could be adapted for Earth-based applications. The present, future-oriented plan is to reuse end-of-life materials (and plastic polymers are among the first candidates) for complete reworking using 3D printers (Fig. 3).

3. Studies on soil plastic polymers in the last 5 years

I searched for articles only the WoS and Scopus (Elsevier) databases starting from 2019. Initially, a broad search was performed using the query: (TITLE(plastic) OR TITLE(plastics)), which returned over 25,000 documents. To narrow the focus, targeted searches were carried out on specific polymers, particularly those linked to the environmental compartment 'soil.' Individual searches were conducted for each polymer listed in the abbreviations, such as (TITLE(polyurethane) AND TITLE-ABS-KEY(soil)). Additionally, focused searches were performed for each topic covered in the review. For example, (TITLE(plastic AND polymer) AND TITLE(blend)). After removing duplicates, I obtained a total of 601 papers (full database available on Zenodo, https://zenodo.org/records/13624642). Of these, 182 papers did not address research involving at least one plastic polymer and its behaviour in soil, while 107 were review articles (actually, the impressive average of 28 published annually, had I not got to the point of writing this umpteenth review on plastics in the soil would have put me off). The analysis focused on the remaining 294 references.

The dataset includes 200 observations for degradation time, with an average of 181 days and high variability (standard deviation of 353 days). Degradation times range from 0.05 to 3600 days, with the 25th percentile at 30 days, the median at 90 days, and the 75th percentile at 180 days. This indicates that most degradation occurs within six months. For the degree of degradation, based on 63 observations, the mean is 53 % (standard deviation of 36 %), with values ranging from 0.5 % to 100 %. The 25th percentile is 13 %, the median is 60 %, and the 75th percentile is 90 %. Most samples show significant degradation. As said before, PE is the most extensively studied polymer, with PLA and PBAT also frequently appearing in research, indicating a rising interest in biodegradable materials. PP, PS, and PVC are moderately studied, while other polymers are examined only occasionally (Fig. 4). Prior to 2018, polymers like PU and PVC received more attention, whereas research on biodegradable polymers was less common.

The median duration of these studies is 90 days, where observed (38 unique values), with a maximum degradation percentage with 99 % being the most frequent degradation value under a pH of 7, but many studies have measured variations over time (indicated as 'various' in table) (Fig. 5). DMAc, CHI and BIO (90–100 %) show almost complete degradation under the conditions studied. PS and PP (>90 %) and BIO (90 %), typically considered less biodegradable, high degradation are due to specific experimental conditions. PLA, PBS and PBAT (>65 %) are also known for their biodegradability. PE (31 %) and PU (11 %), known for their resistance to degradation, align with their chemical stability.

Black plastics present significant challenges in recycling due to the presence of additives such as plasticizers, which can pose health

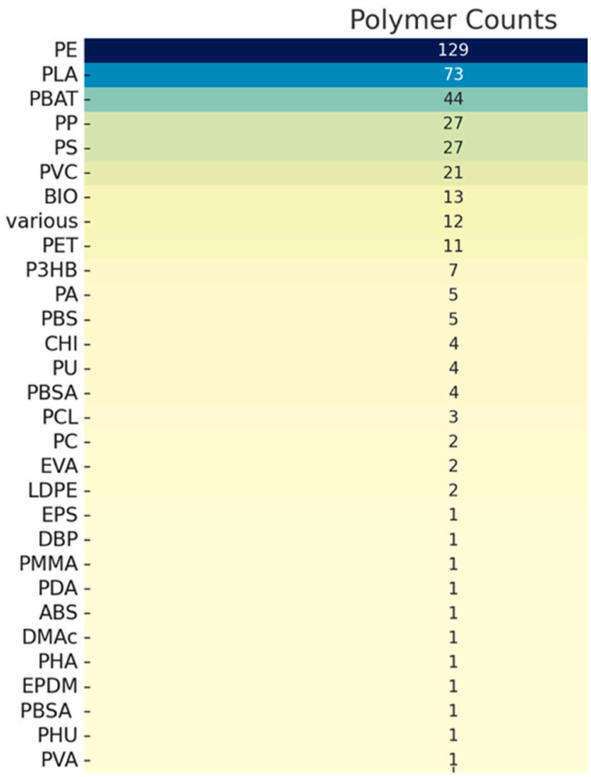

Fig. 4. Polymers studied in the works reviewed from 2019. Various indicates that more than four polymers were considered in the individual study.

risks and make sorting difficult. These plastics are often harder to recycle because conventional imaging systems struggle to distinguish them from other materials. As a result, black plastics are frequently diverted to incineration or landfill.

One third of the papers considered microplastics, 27 papers analysed microplastics in detail, including their chemical speciation or their sizes.

Some studies on plastic polymers also included various co-contaminants. The most studied were PAEs, featured in 13 papers, followed by DEHP. Other contaminants, such as BPA, PHA, and pesticides, were examined less frequently.

Some studies included biota, with five focused on animals like *Eisenia fetida* and *Lumbricus terrestris*, nine on plants including *Zea mays*, *Solanum tuberosum*, *Brassica chinensis*, and *Gossypium hirsutum*, and ten on bacteria and fungi, involving species such as *Bacillus thuringiensis*, *Pseudomonas* spp., *Penicillium citrinum*, and *Aspergillus fumigatus*.

Studies must be replicable, which requires a precise description of the study object. Unfortunately, less than a quarter of the papers reviewed (68 studies) provided geographical coordinates with sufficient precision (to the second) to allow for future resampling. Even more concerning is the naming of the soil: only one-third of the papers (96 studies) specify anything beyond simply "a soil." Of these 96 papers, 17 provided a textural definition (e.g., sandy loam soil), 11 referred to paddy soils, 5 to agricultural soils, and others used generic or regional names such as cinnamon soil or purple soil. Out of the 294, only 21 provided the full soil name (family or series or Reference Soil Group plus qualifiers) according to the USDA Soil Taxonomy [64] or the World Reference Base for Soil Resources [65]. Any less detailed information would be inadequate for replicating or comparing the studies [66].

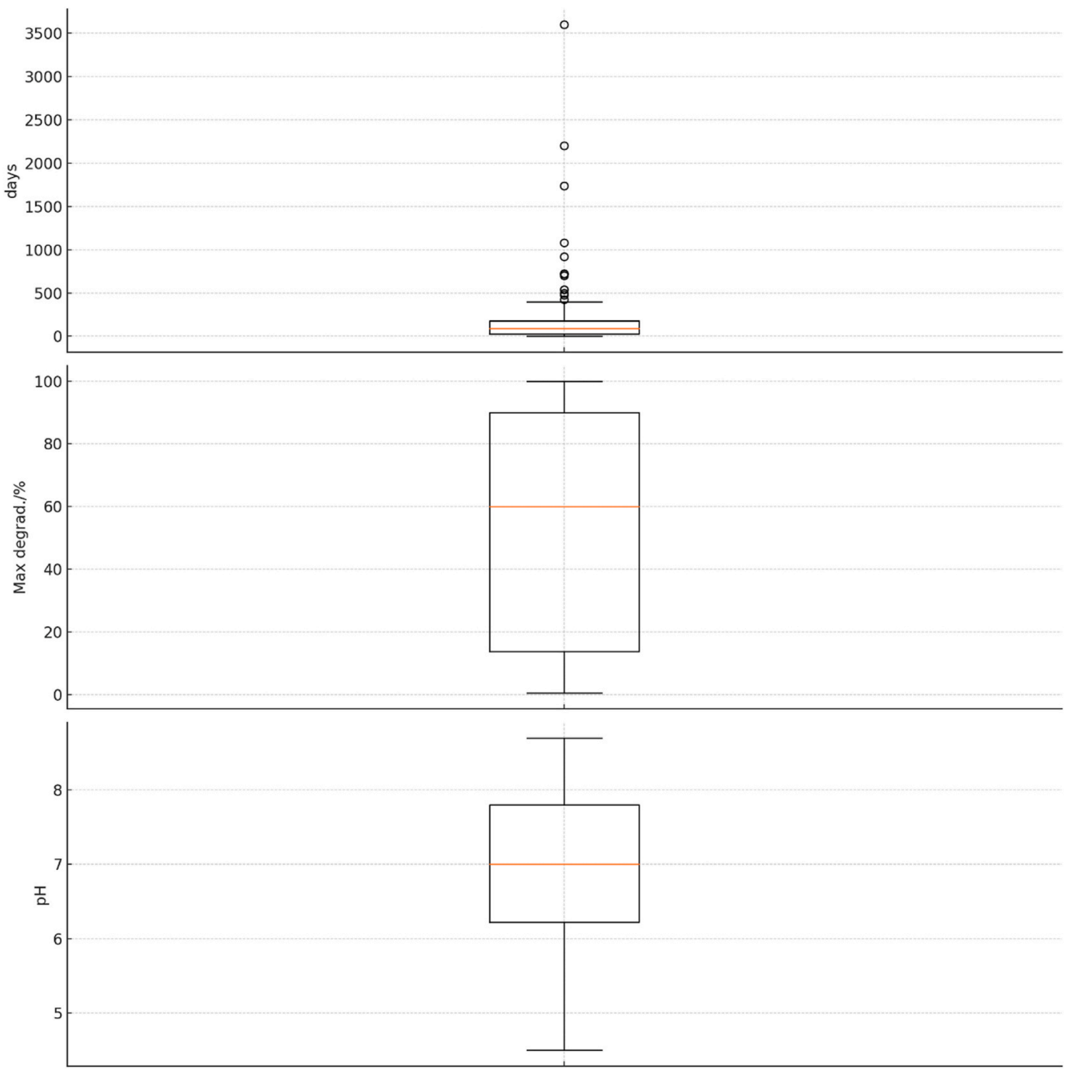

Fig. 5. The experimental conditions in the works reviewed from 2019: box and whiskers diagrams indicating (from the top) incubation days, maxima degradation rate of the polymer studied, and pH.

4. Discussion

4.1. Challenges in recycling black plastics

Black plastics pose significant challenges due to their composition and the presence of harmful additives, such as plasticizers, which can have negative health impacts, making the recycling process more difficult [1,67]. To tackle these issues, imaging systems, including those enhanced by machine learning, have been developed to distinguish between different types of black plastics [68–70]. Once sorted and classified, black plastics, aside from thermovalorization, can potentially be converted into carbon nanotubes through chemical vapor deposition [71]. However, this promising approach is rarely applicable in real-world agricultural settings.

4.2. Advancements and challenges in the blending of recycled polymers

One of the major challenges in recycling plastic polymers is dealing with mixtures (Fig. 6). Similar to the challenges faced in glass recycling, particularly with color separation, grouping all types of plastics together often leads to the only feasible outcome: waste-to-energy processing. While more sustainable approaches are possible, they require sorting polymers individually. A significant advancement would be to enable blending of different polymers. With the use of compatibilizers, nanofillers, and advanced processing techniques, the blending of recycled polymers is becoming increasingly feasible.

Blending different types of polymers, especially those that are typically immiscible, often results in materials with poor mechanical properties. However, preserving the mechanical properties of the polymers during blending is crucial. For instance, studies by Titone et al. [72] and Jubinville et al. [73] suggest that mechanical recycling of polymer blends can retain material properties even after multiple reprocessing cycles. Cecon et al. [74] demonstrated that blending post-consumer recycled polyethylene (rPE) with various virgin polyethylene grades can produce materials with enhanced mechanical properties. Similarly, Marotta et al. [75] showed that adding organo-modified clay nanoparticles to a ternary blend of high-density polyethylene (HDPE), polypropylene (PP), and PET can refine the microstructure, leading to improved mechanical properties and thermal stability. Pimbert et al. [76] discuss a fluorinated polymer blends as cladding material.

Mimicking the natural formation of coal, hydrothermal carbonization—where organic materials are converted into a carbon-rich solid (e.g., hydrochar) under high temperature and pressure in the presence of water—has been shown to enhance the mechanical strength of treated recycled blends, according to studies by Goli and Singh [77] and Kim et al. [78]. These researchers concluded that such treated blends could be classified as composites due to their enhanced mechanical properties.

However, significant bottlenecks remain, particularly concerning the compatibility of recycled polymers and the application of newly formulated polymers. Compatibility between different polymers is a critical issue. Ha et al. [79] highlighted this, while Wu et al. [80] proposed reactive extrusion as a method to improve the toughness of biodegradable polymer blends by optimizing the compatibility between components. Vouvoudi et al. [81] explored catalytic pyrolysis of polymer blends to enhance the environmental sustainability of recycling waste electrical and electronic equipment (WEEE). Similarly, Nizamuddin et al. [82] investigated the use of

Fig. 6. Recycling plastic polymers faces challenges, particularly with blending different types due to compatibility issues, often resulting in final poor (mechanical) properties. Advances in using compatibilizers, nanofillers, and techniques like hydrothermal carbonization show promise in improving these properties, but practical application and environmental concerns, such as VOC emissions, remain significant hurdles. (DALL·E image).

PE-g-MA and sulfur as compatibilizers in low-density polyethylene (LDPE) blends. Research by Arman et al. [83] and Dib et al. [84] further demonstrated that incorporating carbon nanotubes and nanofillers into recycled blends, such as rPET or rHDPE, can significantly improve mechanical properties.

Despite the potential, applying polymer blends in practical applications remains challenging. Pimbert et al. [76] explored fluorinated polymer blends for use as cladding materials in optical fibers, while Gasparini et al. [85] studied ternary polymer blends for solar cells. In the automotive industry, Vieyra et al. [86] provided examples of polymer blends, and Zander et al. [87] focused on using recycled polypropylene (rPP) in 3D printing.

Another key concern with recycled plastics, is the potential emission of volatile organic compounds (VOCs) and other hazardous substances during re-processing. In the case of bitumen, Boom et al. [88] found that incorporating recycled plastics into can reduce overall emissions, depending on the type and source of the recycled material used.

4.3. Plastic end-of-life: strategies for disposal and reuse

The consequences of a plastic object's EoL depend on when and how it transitions from being seen as a resource to being regarded as waste (Fig. 7). Once an object has fulfilled its intended purpose, the ideal EoL option is reuse [22]. Recycling, while slightly less preferable, remains effective. Plastic polymers vary widely in characteristics and market value—for example, polyvinyl chloride (PVC) is valued at half the price of polyurethane (PU) per tonne. This makes separation essential for recycling, though it can be costly. As a result, immiscible polymer blends and polymer blending are rapidly growing in polymer engineering to create innovative materials

Fig. 7. Separate collection of glass in Brussels. Glass, one of the oldest synthetic materials, dates to the third millennium BC, while plastic is a much more recent invention from the last century. Both glass and plastic share the ability to be recycled through cooling and reversible transitions, but glass can be recycled almost infinitely, whereas plastics often suffer from downcycling due to polymer diversity and immiscibility [1]. Plastics might ultimately be used for energy production, unlike glass. For both materials, the 3R strategy (reduce, reuse, recycle) would be the most effective waste management approach. Glass reuse is feasible for certain beverage containers but faces challenges in sanitation and durability. The reduction strategy applies similarly to glass and plastic, aiming to minimize material use in products [22]. Recycling for glass and plastic can involve either open-loop (where EoL materials are transformed into new products) or closed-loop processes (where materials are reused in their original form). Recycling all recyclable materials would be an excellent way forward. Glass is a good example, but its optimal (economically sustainable) recycling occurs if colours are separated. Analogy with plastics which, if separated by polymer, could be recycled very easily. Unrealistic scenario since, globally, only 19 % of municipal solid waste is recycled [97]. And, unfortunately, as nations become more affluent, they usually see greater industrial and urban development, alterations in housing and consumption habits, and a broader selection of products available, contributing to an increase in the average amount of waste produced per individual [98]. Recent research focuses on addressing plastic waste through innovative conversion methods into valuable chemicals [99,100] and, thinking positively, evaluating pathways toward achieving zero plastic pollution [101].

[22].

Composting is applicable only for bio-based polymers, followed by energy conversion. If the common yet prohibited practice of direct environmental disposal didn't exist, landfill burial would be deemed the least favorable option. In contrast, upcycling, which transforms waste into valuable products, is considered the best [22]. In the case of plastics, an open-loop process may end in road building or building materials, but compatibilization is the key to the success of plastics recycling [23,89]. The agricultural sector, for instance, demonstrates that farmers' decisions to join recycling programs are heavily influenced by costs and the availability of alternatives. Understanding the economic viability of these alternatives is essential for promoting more sustainable practices. Reorganizing the plastic value chain with a focus on the circular economy is crucial and requires investments and coordinated efforts from all stakeholders to develop thriving markets for recycled plastics [22].

4.4. Implications of the new findings

In recent years, significant progress has been made in research, along with growing awareness of the problem. Advances have also been achieved in legislation, notably the European Directive on single-use plastics (Directive (EU) 2019/904). Other countries, including Australia, China, Canada, Japan, India, Kenya, New Zealand, South Korea, the UK, and some US states (California, Maine, New York) have enacted similar legislations targeting the reduction of single-use plastics.

Extensive research efforts have generated a vast amount of results. However, as discussed in the previous chapter, many of these results face significant challenges when it comes to comparison and replication. This raises concerns that these efforts may ultimately be ineffective in practical applications. Methodological advances, particularly in studying microplastics in soil, have demonstrated good efficacy in the laboratory but are not yet feasible in real-world settings due to being too complex, costly, or resource-intensive.

5. Future research directions

The number of scientific papers dealing with plastics has risen dramatically in the last five years, exceeding 40,000 articles per year surveyed by WoS or 50,000 by Scopus. In 2000 they were one fifth. Unfortunately, the potential for replicating these studies has not improved equally. This issue is particularly evident in research involving plastic polymers and their relation to soil. While many studies mention soil in their titles, they often fail to provide adequate descriptions. The source of the soil is not specified, its taxonomic classification is omitted, and only the most thorough studies mention details such as texture or pH. It is likely that most authors would be alarmed to learn that the same polymer was tested on an unspecified animal or plant, as this leaves them unable to determine which species is being referenced. In its triviality, the possibility of replicating the studies by obtaining all the necessary information in the Materials and Methods section would be a big step forward.

The uncontrolled presence of plastic in the environment generates pollution. This is a certainty that no longer needs to be explored, in general. The numerical awareness of the polymers that can potentially be released into the environment, on the other hand, is still a quite unexplored field. While on the one hand, there is an increase in work providing general numbers, because they are collected, e.g. by remote sensing techniques [90]. Very rare are the quantifications: how many grams of a certain polymer are introduced into the environment to produce a certain food, for example [21]. Both approaches are valid, but in the future, detailed knowledge will improve decision-making. While understanding the number of microplastics per square meter in a given area certainly raises awareness, making effective management decisions requires precise and specific data about the chemical species involved.

Hot topics are addressing plastic pollution across various ecosystems, beginning with agricultural systems [39] and extending to water bodies [91]. The potential of microorganisms [92] and enzyme-based biocatalysis to degrade various types of plastics is gaining attention. Additionally, there is growing concern over the long-term consequences of microplastic pollution [43]. Opportunities for sustainable materials management are emerging, ranging from waste-to-energy conversion strategies [93] to the economic feasibility of integrating pyrolysis [94], electrocatalysis, and the selective conversion of diverse plastic materials into valuable chemicals [95]. These efforts are crucial for advancing a circular economy for plastics and achieving sustainability [96].

In terms of policy, while extended producers responsibility (EPR) schemes have been effective in raising funds for waste management, they have been less successful in incentivizing waste reduction. The UNEP [97,98] report suggests that fiscal policies need to be combined with bans on single-use plastics and other problematic materials to be effective.

6. Conclusion

Even in the best-case scenario with strong management, the total amount of plastic will increase in the coming decades. To address this, strategies include upstream measures, such as reducing demand and improving packaging, and downstream measures, such as collection and recycling. Plastic pollution, particularly microplastics, poses a growing threat to soil ecosystems. Although efforts to introduce biodegradable alternatives show promise, they bring their own set of environmental challenges. The decision to use biodegradable plastics or conventional polymers in soil applications involves balancing immediate environmental benefits (e.g., reduced waste accumulation) with potential long-term impacts on soil ecosystems. Biodegradable plastics offer a promising alternative to mitigate plastic waste, but their benefits are contingent on full biodegradation and minimal environmental toxicity. Conventional plastics, while durable, contribute to long-term environmental pollution, particularly through the formation of microplastics. Sustainable solutions require a comprehensive approach, combining material innovation, improved waste management infrastructure, and policies to encourage responsible production, use, and disposal.

It is essential to standardize degradation indicators to ensure consistency across studies and regions. Technological innovations such as chemical recycling and compatibilizers can help reduce microplastic generation during recycling, while policies like Extended Producer Responsibility (EPR) encourage manufacturers to adopt sustainable practices. A circular economy, combined with collaborative efforts between governments, industries, and researchers, is critical to effectively managing plastic waste and minimizing its impact on soil health.

There are inherent bottlenecks and contradictions. For example, rigid plastics are easier to recycle due to their straightforward collection and sorting. But the more rigid they are, the more, in handling, they can produce microplastics. So, reorganizing the plastic value chain from a circular economy perspective requires investment and collaboration among stakeholders to create robust markets for recycled plastics. Upstream efforts involve industries working with public stakeholders to minimize material use and tackle packaging issues. A stark example is bitumen additives: usually, the plastic used in their big bags is not reused or recycled but ends up in landfills as it is cheaper to consider it as waste.

Plastic polymers were originally designed for durability, intended to last as long as possible. However, after 70 years of widespread use, we've realized that while plastic doesn't degrade, it breaks apart, creating various issues. The core challenge isn't about finding ways to degrade plastic in the environment, especially in soil, but rather preventing it from breaking down into micro-particles or releasing harmful chemicals. If plastic remains intact, it poses no greater risk to soil than other waste materials like glass or metal. Ironically, the solution may be to make plastic less degradable and less prone to fragmentation.

Fiscal policies, combined with bans on single-use plastics, can further drive the market for recycled polymers. Collaboration between industries and governments can lead to the development of new technologies and business models for plastic waste management. The European Union's Circular Economy Action Plan has set ambitious recycling targets and promoted EPR schemes, leading to higher recycling rates and innovation in recycled product markets across member states. Other successful stories are projects in India and the Netherlands have used recycled plastics to create more durable and sustainable roads.

Data availability statement

The full database used in this study is publicly available on Zenodo and can be accessed at https://zenodo.org/records/13624642.

Declaration of competing interest

The author declares the following financial interests/personal relationships which may be considered as potential competing interests: He is a Section Editor of this journal (Soil Science section).

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Fig. 1 in this article was previously published in Current Opinion in Chemical Engineering 32, 100681 by Galati and Scalenghe. Copyright Elsevier (2021).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40647.

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