



Review

Plastics in Agricultural and Urban Soils: Interactions with Plants, Micro-Organisms, Inorganic and Organic Pollutants: An Overview of Polyethylene (PE) Litter

Pavlos Tziourrou^{1,2} and Evangelia E. Golia^{1,*} ¹ Soil Science Laboratory, School of Agriculture, Faculty of Agriculture, Forestry and Natural Environment, Aristotle University of Thessaloniki, University Campus, 54124 Thessaloniki, Greece² Department of Chemistry, University of Patras, 26500 Rio, Greece

* Correspondence: egolia@auth.gr; Tel.: +30-23-1099-8809

Abstract: Over the last few decades, different types of plastics have been found in different soil types with documented or potential negative effects on the environment, the flora and fauna inhabiting the soils, and subsequently human health. This article is a global review of the consequences of the interactions of plastics with soil, plants, soil microbes, and organic or inorganic pollutants depending on land use. It focuses on the various types of polyethylene, a widely used material with a strong presence in both agricultural and urban soils. Although the chemical formula $(C_2H_4)_n$ remains the same in its various classifications, the chemical behavior of polyethylene in soil varies and directly depends on its density, branching, crystallinity, and relative molecular mass, resulting in many and various differences in the properties but also in the behavior of the two main forms of polyethylene, low and high density. However, beyond the chemical composition of plastics, the climatic conditions that apply in both urban and rural areas determine the degree of corrosion as well as their shape and size, also affecting the chemical reactions that directly or indirectly affect them. In agricultural soils, plants and the microbiome present mainly in the rhizosphere seem to dramatically influence the behavior of plastics, where the interaction of all these parameters leads to changes in the availability of nutrients (phosphorus and potassium), the percentage of organic matter and the nitrogen cycle. In urban soils, the increase in temperature and decrease in humidity are the main parameters that determine the adsorption of heavy metals and organic pollutants on the surface of plastics. Although the presence of plastics is considered inevitable, perhaps a more thorough study of them will lead to a reduction in the risks of pollution in urban and rural environments. This research provides a promising perspective on the potential contribution of MP PEs to the sustainable management of soil systems.

Keywords: climatic conditions; LDLE; HDPE; microplastics; polyethylene waste; crystallinity

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1. Introduction

Plastics exist in our everyday life, facilitating different parts in our lives. However, there are cases where plastics end up having negative effects both on the environment, e.g., ingestion by organisms [1], and by extension on human health, e.g., carcinogenesis [2]. Their reckless use results in their presence in the atmosphere, in water bodies [3], in the soil [4] and in glaciers [5], as well as their existence as Anthropocene fossils [6]. It has been estimated that more plastic litter than fish will be found in the marine environment by 2050 (by weight) [7]; a plastic bag in the deepest part of the Earth was also observed [8].

Different environments (atmosphere, hydrosphere, land, etc.) are interconnected and dynamic environments [9]. As a result, plastics are transferred from one system to another [10,11]. In addition to the medium (water, air, soil), the presence of plastic in a terrestrial (e.g., coastal) area also depends on land uses, e.g., if it is an industrial, urban, or fishing area [12]. Plastics then interact with other parameters, such as different pollutants

like heavy metals in soil [13], weather conditions, microorganisms [14], vegetation [15], and so on (Figure 1). Other important parameters in the context of interactions are the type of plastic, its shape, size [16], surface properties (e.g., roughness) [17] and other mechanical properties, and physical properties as well as chemical, such as additives; plastics contain many elements that are not chemically attached to the polymer matrix, such as unreacted monomers, residual processing aids, and additives [18].

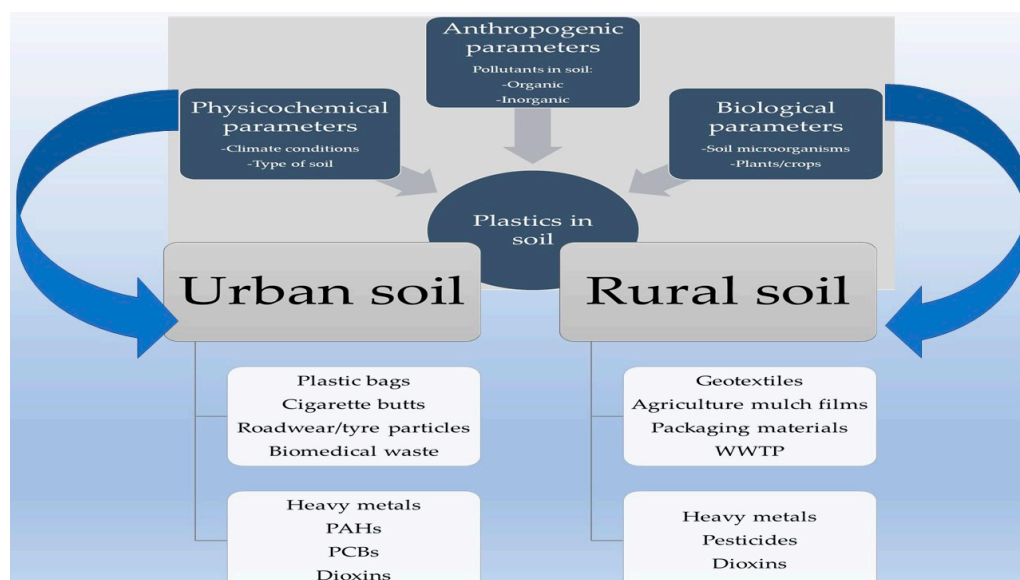


Figure 1. Interactions of plastics with organic/inorganic pollutants and natural parameters in soil conditions.

Estuaries, the global ocean, and freshwater aquatic ecosystems have been linked to significant levels of microplastic pollution [7,19]. As reported by Meijer et al. [20], over a thousand rivers are the source of 80% of the riverine plastic released into the marine environment worldwide. However, it is mentioned that there are more microplastics (MPs) in terrestrial ecosystems than in the marine column, making them important reservoirs [21]. According to He et al. [22], 51.49% of papers on plastic litter from 2014 to 2018 focused on aquatic environments, compared to just 3.86% on soils. Approximately 4–23 times as much plastic is deposited in soils as there is in the world’s marine environment, although little is known about the ecological effects, for instance on plant growth [23], of plastic litter on terrestrial ecosystems (soil) [24]. As an example, the biggest terrestrial biomes, i.e., dryland, cover 41% of the planet’s terrestrial surface, supporting over 38% of the human population worldwide [16,25], and could be seriously threatened by an increasing concentration of MPs in the soil [16].

Soil can be defined as the uppermost layer of the crust of the Earth based on the ISO [26], altered by different processes such as physical, chemical, and biological, as well as weather conditions. Specifically, in rural environments, the physical body of soil is affected by the uncontrolled use of animal manure, fertilizers, and different solid and liquid wastes in agriculture [27]. An example research has indicated that adding plastics (polyethylene) resulted in a reduction in soil organic carbon (OC), which is crucial for plant nutrition and soil fertility [13,28]. Maintaining the quality of the soil environment is crucial for ensuring the integrity of soils, the health of the flora and fauna growing within them, preserving the quality of the underground aquifer, and increasing the quantity and quality of safe products [29].

In recent years, efforts have been made to assess the potential risks posed by the presence of microplastics in soil systems. A variety of results can be seen from the use of polyethylene. Furthermore, the current article is a review of the types of different interactions in soil associated with polyethylene pollutants. Both the type of soil (type of

silt, grain size, soil aggregation) and the presence of other environmental conditions, such as organic composition, pH, humidity, temperature, and others, are factors of different interactions and therefore impacts of plastics. Focused on the biosphere [the relatively very thin layer of the Earth's soil surface, where life has been observed], it aims to summarize examples from various scientific studies by recording generalized examples, summarizing the different effects of each type of interaction.

2. Methodology

The present study is a review paper comprising articles from the last decade (2013–2023), which focuses on specific polyethylene types and not on the general term of PE; thus, the two types of polyethylene, low- (LDPE) and high-density polymer (HDPE) were mainly included, as they are applied to both agricultural and urban soils. Articles from MDPI, Springer, Elsevier, ACS, Frontiers, and Plos One academic publishing companies were mainly chosen; one article from Environment Research Center, University of Babylon, Iraq, and one from Lifescience Global (a Canadian publishing company) were also used.

Figure 2 below displays the publishers that included the articles that satisfied the two filters: a. the two types of polyethylene microplastics and b. the LDPE and HDPE microplastics found in urban and rural soils.

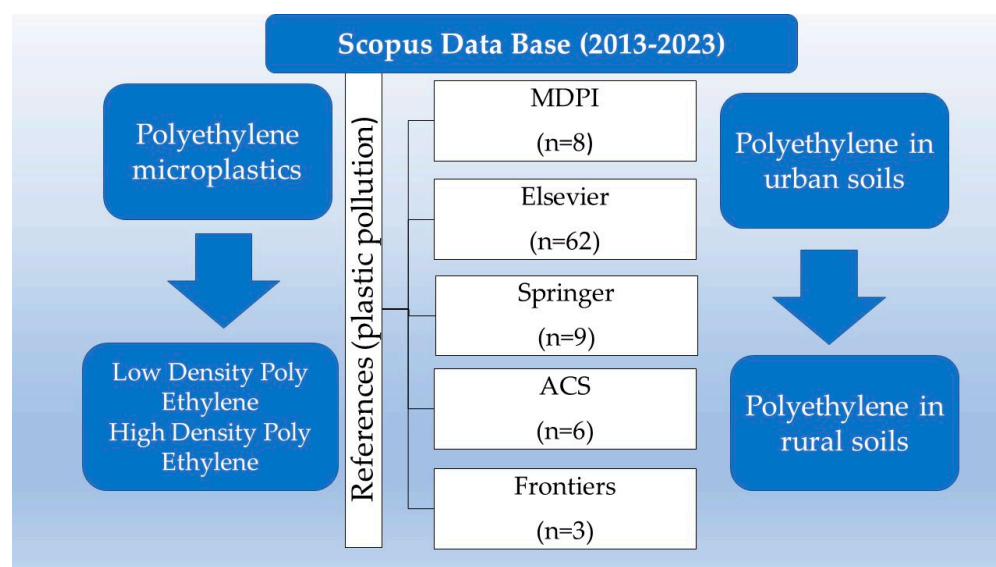


Figure 2. Identification methodology of published articles and the filters used for this research.

From the above Figure, it is clear that the largest percentage, equal to 68.8% of the articles, that met the survey criteria came from Elsevier. It should also be noted that whether the articles were open access or not was not a determining factor in the selection of articles. All articles were read thoroughly and their data were compiled in an Excel file. Statistical processing of the data was then performed and the charts were constructed, which are presented later in this paper.

3. Sources of the Main Plastics in the Terrestrial Environments

The study of plastic litter in the terrestrial environment is still in its early stages [30]. Diverse practices in urban and rural places exist and thus various sources of plastic pollution with different consequences were recorded. Table 1 shows the main entrance of plastics in two categories of soil (urban and rural [29]). There are cases where the two categories of sources overlap, due to the presence of common plastic wastes, for instance, plastic bags [31].

3.1. Rural Soils

Vegetables and grains are supplied by rural areas around cities to both urban and rural populations, and the condition of the soil there affects food security [32,33]. Thus, agriculture practices such as plastic mulch films are used; they are extensively utilized in crop production, making up around 50% of the mass of all agricultural plastics [34], starting from 1991 [35]. Geotextiles, flexible textile materials with synthetic fibers, as well as geomembranes, thin sheets of impervious plastic materials, are geosynthetic materials for applications in landfills [36]. Geotextiles typically provide filtration and thus, they are used in crops. Table 1 further summarizes agricultural practices that act as sources of MPs in agricultural areas.

A major source of MPs, i.e., the wastewater used in agricultural soil from urban origin, was mentioned in a viewpoint article by Nizzetto et al. [21]. According to Edo et al. [37], a wastewater treatment plant (WWTP) discharged 300 million plastic debris per day, and the usage of sludge as a soil supplement resulted in 10^{13} microplastic particles being loaded in agricultural soils annually; conversely, in situations where there is an abundance of organic matter and biofilm [38], MPs may function as antibiotic transporters [39]. Although urban-origin bags (single-use) are frequently seen as litter in both urban and rural areas, the majority of them eventually end up in landfills, mostly from supermarkets [31].

3.2. Urban Soils

Urban regions are significant factors in the production of MPs (Table 1) and their entry into the aquatic environments [40], such as the primary MPs from the synthetic fabric washing process [41]. Plastic litter is thought to be transported into freshwater by urban rainfall runoff [42]. Nevertheless, plastic waste is used in bituminous mixes to enhance the properties of the bituminous pavement [43]. However, studies have found that urban MPs from road wear particulates as well as tires contribute significantly to microplastic pollution [30].

One of the plastic goods that is most commonly utilized is plastic bags [44]. Based on The World Counts [45], over 5 trillion plastic bags in annual consumption worldwide were estimated. The majority of them are made both from HDPE and LDPE materials [46]. Specifically, ~500 billion units per year around the world for LDPE bags are produced [47]. In 2014, major supermarkets in England gave away 7.6 billion single-use plastic bags (HDPE bags used in almost all UK supermarkets) to customers, contributing to urban pollution [31].

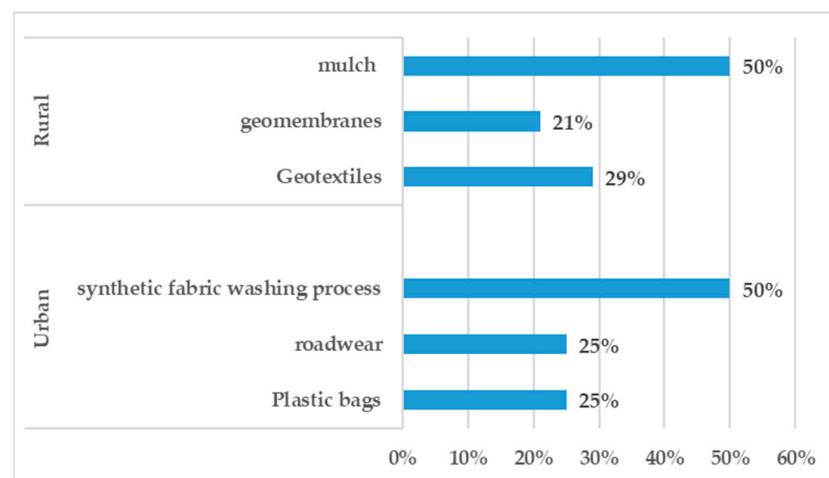
A lot of goods, including food, detergents, chemicals, cosmetics, and medication, are packages also made from synthetic polymers. The most common polymers used in packaging include nylons, polybutylene terephthalate, polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PU), polyethylene terephthalate (PET), and PE [low-density polyethylene (LDPE), high-density polyethylene (HDPE), medium-density polyethylene (MDPE), and linear low-density polyethylene (LLDPE)] [48].

The recent coronavirus disease (COVID-19) pandemic has increased the demand for single-use plastics, increasing pressure on the already uncontrollable problem [49]. According to Benson et al. [50], syringes, surgical face masks, disposal blades and scalpels, face shields, latex gloves, surgical and isolation gowns, shoe covers, sanitizer containers, and waterproof aprons are plastic-based biomedical waste that has emerged during the COVID-19 pandemic. The pandemic-related litter not only caused negative effects on terrestrial ecosystems such as ingestion by animals [51] but urban areas were also sources of pollution for coasts and marine environments [49,52].

In Figure 3, the sources of microplastics of polyethylene in urban and agricultural soils are listed. In agricultural soils, the majority, as shown in the published articles, is mulch, then geotextiles and finally geomembranes. In urban soils, 50% of the published articles refer to the cleaning and washing processes of synthetic-plastic fabrics as sources of microplastic PE.

Table 1. Summary table of the sources of plastics and other pollutants in the terrestrial system.

Various Types of Synthetic Plastic Litter in the Global System (Atmosphere, Aquatic and Terrestrial Environments). Natural Parameters [Microorganisms, Physicochemical Parameters (e.g., Weather and Soil Conditions)]	
Urban Solis	Rural Soils
Main Sources of Plastics	Main Sources of Plastics
Plastic bags, cigarette butts, roadwear and tire particles, COVID-19 plastics (disposable masks and their cases, single-use gloves), stormwater in catchments, artificial turf, carpets, particles vented from domestic tumble driers, microplastics due to synthetic fabric washing process, biomedical plastics.	Geotextiles, geomembranes, agriculture mulch films (typically from LDPE, PVC, or ethylene–vinyl acetate copolymers), insect glue trap plastics, abraded plastic from string trimmers, plant clips, nursery pot trays, agricultural packaging materials (e.g., fertilizer and storage bags, flexible bulk containers, crates, containers for pesticides), the usage of sludge as a soil from wastewater treatment plants (WWTPs).
Pollutants [27,53,54]	Pollutants [54–56]
Heavy metals [Cadmium (Cd), antimony (Sb), and Pb are continuing to increase due to traffic (e.g., lead (Pb) added to petrol)]	Heavy metals [Natural sources and anthropogenic inputs (Sources: fertilizers and pesticides, wastewater irrigation, sewage sludge application, and atmospheric deposition)]
Polycyclic aromatic hydrocarbons (PAHs) [due to industrial activities (burning hydrocarbon fuels) and from road traffic]	Pesticides (e.g., insecticides, herbicides, and fungicides)
Polychlorinated biphenyls (PCBs) [primary sources in cities: used in the manufacture of carbonless copy paper (as heat transfer fluids, etc.)]	Antibiotics (Sources: municipal wastewater, animal manure, sewage sludge, and biosolids)
Dioxins [wide variety of sources (by-products of the processes in which the chlorine content is involved)]	Dioxins [From the consequences of war and human activities (examples: fuel combustion, metal production, pesticide production and use, waste incineration, accidental fires, landfill disposal, combustion, and herbicide runoff in agricultural uses)].
Platinum group elements (PGEs) (in road dust)	
Rare earth elements [Gadolinium (Gd) due to hospital effluents]	

**Figure 3.** Percentage distribution of published papers addressing the sources of microplastic PE in rural and urban soils.

4. Effects of Polyethylene Litter on Different Soil Types

A strong interaction is established between MPs and soils, as soils can influence the chemical behavior of plastics, yet MPs can also modify the physicochemical properties of soils. The chemical composition, proportion, and dimensions of the MPs affect the properties of the soil, including the soil microbiota [57–59], as previously investigated.

In addition, MPs in both urban and agricultural soils have received the attention and interest of the scientific community due to their wide distribution and the variety of chemical reactions that can take place on their surface due to their strong adsorption capacity [60]. MPs have been studied in many different soil types and the results show that the soil type can influence the chemical behavior and toxicity of MPs [61]. The researchers Liu et al. [62] examined how soil particles and naturally occurring carbon were affected by the excessively thick layer of MP pollution at various soil depths. They found that the total quantity of soil aggregates was raised by the plastic contamination layer (PCL). Furthermore, ref. [63] observed that a significant increase in soil respiration is repeatable in multiple habitats, and the aging of MPs in the environment may have immediate implications for climate change and evolutionary ramifications for the forest soil microbiome. In saline–alkaline soils, ref. [64] found that as MP pollution rises, the coastal saline–alkali land impacted by agricultural production and seawater may become contaminated with MPs. Their findings showed that MP type, dose, and size significantly influenced changes in soil properties, soil microbial diversity, and microbial community composition in saline–alkaline soils. There were also strong correlations found between changes in soil properties and changes in bacterial and fungal diversity.

5. Organic and Inorganic Pollutants in the Terrestrial Environments

Jie et al. [65] investigated soil contaminants and tried to classify them in order to better understand their chemical behavior and predict their environmental fate. Contaminants existing in the environment, notably in soil, are divided into two categories based on their chemical composition: inorganic and organic pollutants.

PE mulch is used in a variety of field crops to suppress weeds and conserve water in crop production and landscaping. However, it is possible that numerous substances may be adsorbed on it, either nutritive or toxic, inorganic or organic. Inorganic nutrients such as nitrogen, potassium, or phosphorus are typically mentioned, while organic ones include agricultural products or herbicides, fungicides, and other plant protection agents [23].

Presented in the following Figure 4 is the percentage of published articles that refer to the three most important pollutants that coexist and are likely to interact with MPPEs in agricultural and urban soils.

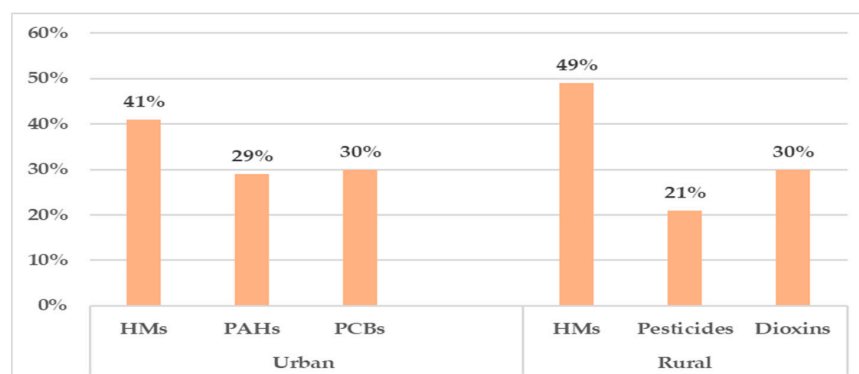


Figure 4. Percentages of published articles on pollutants in urban and agricultural soils.

Inorganic pollutants are mainly heavy metals, which are primarily present in ionic form both on the solid surface of soils as well as in the soil solution [66]. Heavy metals are defined as metal elements with an atomic density greater than 5 g/cm³ [67]. They are subdivided into two distinct groups: trace elements, which are essential in small quantities

for the smooth functioning of living organisms (plant and animal), such as copper (Cu) and zinc (Zn), and toxic elements, such as cadmium (Cd), lead (Pb), and mercury (Hg) [66,67]. Although trace elements in small amounts are essential for the growth of animals and plants, they can still cause considerable impairment once they exceed a certain value, which is different for each metal and individual organism. For this reason, in recent decades, the term increasingly used is Potential Toxic Elements (PTEs) [66,67].

In addition to metals, there are also some metalloid elements, such as arsenic (As). In addition to metals and metalloids, an important category of inorganic pollutants are non-metallic elements, such as nitrate (NO_3^-), ammonia (NH_4^+), and nitrite (NO_2^-) ions, phosphate (PO_4^{3-}), cyanide (CN^-), sulfur (S^{2-}), and many others [66,67].

PTEs are able to participate in a variety of chemical reactions with soil components, such as soil organic matter, as well as with other components of the soil system [68]. They can also occur in different oxidation states, such as arsenic, which is in the form of a trivalent or pentavalent ion, and chromium in the form of a trivalent or hexavalent ion [69].

Organic pollutants can be divided into several classes, again depending on their chemical composition and degree of risk. They can be distinguished on the basis of their halogen content, with halogenated (e.g., chloroform) and non-halogenated organic compounds (e.g., methane) forming the two groups of organic pollutants. In addition, pollutants can be further separated on the basis of their carbon chain. That is, depending on whether their carbon chain is saturated (single bonds between carbon atoms (e.g., butane)) or unsaturated (multiple bonds between carbon atoms). In addition, there are also aromatic compounds, in which there are one or more aromatic rings of one of their molecules (such as polycyclic aromatic hydrocarbons, PAHs) [68].

Another organic pollutant that has attracted scientists' attention and is considered an emerging risk is polymers or plastics that are present in large quantities in soils in micro-dimensions (<5 mm) [70].

6. Physical (Environmental) Impact on Polyethylene in Soil Medium

Figure 5 provides an overview of the mechanisms involved in the various interactions between plants, microorganisms, the soil solid surface, and the soil solution with PE microplastics.

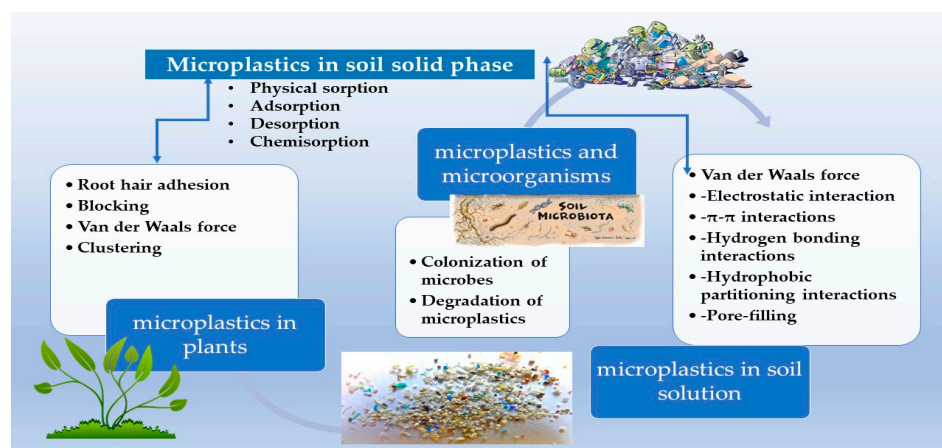


Figure 5. An overview of the mechanisms involved in the various interactions between plants, microorganisms, the soil solid surface, and the soil solution with PE microplastics.

The physical or environmental factors prevailing in the medium containing the MPs are critical parameters that govern their behavior and can modify their robustness and their duration or lifetime. Hou et al. [71] were perturbed about the effect of climatic changes, as they may accelerate the erosion of plastics used in agricultural soils and aggravate them. In their study, seven types of soil amendments were studied and only two were proposed, which could be used to replace current commercial soil amendments, mainly due to their

competitive cost and low environmental impact. Fa et al. [72] further studied the effect of light and heat on the weathering rate of PE, using catalysts and thermo-oxidant additives. Over the past 20 years, the effect of solar radiation on LDPE, the most widely used covering material in Mediterranean countries, has puzzled the researchers Briassoulis et al. [73]. The exposure of the LDPE film to changing weather conditions was studied and its chemical structure appeared to be affected as well as its mechanical and physical properties.

Figure 6 displays the percentages of articles that report the parameters that are able to modify the processes of corrosion and the variation of the properties of MPPEs of both types (LDPE and HDPE). Solar radiation, based on the works of the researchers, seems to play a decisive factor among the physical parameters that influence the behavior and the mechanisms of action of polyethylene microplastics. In agricultural soils, however, microorganisms seem to take the baton, as 50% of the papers refer to them.

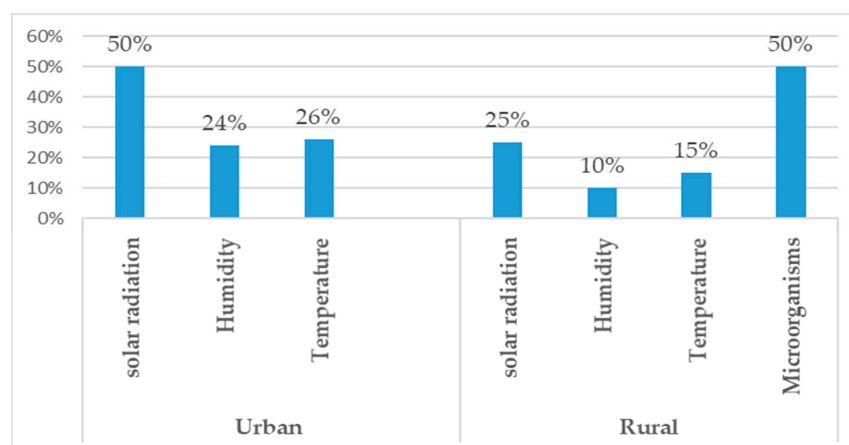


Figure 6. Proportions of the articles referring to the physical parameters affecting MPPEs in urban and rural soils.

Ghatge et al. [74] investigated the environmental parameters that can induce PE degradation. Furthermore, it is suggested that ^{13}C -polyethylene degradation will cause increased production of ^{13}C -labeled metabolites, such as CO_2 emissions, over the course of an incubation period. The researchers Eubeler et al. [75] report, in a review paper, that the degradation of polymerized alkanes can be accelerated by the effect of ultraviolet (UV) radiation. In experiments carried out on compost, corrosion was investigated in ethylene–propylene copolymers, low-density PE (LDPE), and polypropylene (PP) films. Although degradation increased with increasing exposure time, each polymer exhibited different final behaviors. LDPE, after 6 months of exposure, was the most durable polymer. The investigators Shelciya et al. [76] experimented on the decomposition rates of LDPE, polystyrene (PS), and PE with styrene (PE-ST) blends in aqueous media under the influence of UV radiation. It was evidenced by their study that the presence of water caused a significant retardation in the corrosion. Ding et al. [77] revealed that the aging mechanism of PE MPs is significantly affected by the ambient temperature, as they conducted experiments at different temperatures. Upon increasing the temperature, the amount of organic substances that could adsorb onto the plastics or degrade the organic contaminants that interact with the soil plastics changed. Furthermore, Zhang et al. [78] investigated the impact of PE and biodegradable microplastic aging on soil organic matter in soils with different land-use types.

The presence of microorganisms is crucial for the corrosion of PE [79]. Investigations have shown that the microorganisms *Streptomyces* sp. and *Actinomycetes* sp. have the potential to infect and corrode PE, yet it seems that the corrosion is slight and very slow [80]. However, many studies highlight the fact that environmental factors can activate or inactivate the microbiota and interfere indirectly or directly with the corrosion of PE plastics [81,82].

According to Balasubramanian et al. [83], a significant process takes place in the soil when PE remains for a long time, and with the contribution of environmental factors (physical and chemical), it is possible to enhance microbial activity. HDPE is generally resistant to microbial degradation. Microbial degradation does not take place and occurs very slowly. However, when environmental factors change, microbes adapt and, through natural evolution, start to consume PE, since HDPE acts as an excellent source of carbon. That is, the microbes have to remodel their metabolism and adapt in order to survive [74].

However, the simultaneous presence of UV, potassium permanganate, a HCl acidic environment, citric acid, and an increasing thermal energy supply led to the initiation of degradation, indicating that environmental factors (physical and chemical) play an important role in the corrosion of PE microorganisms [84]. Moreover, Danso et al. [85] investigated not only the effect of environmental and biotechnological conditions that can activate microorganisms, so that they could in turn degrade and corrode plastics, but they also investigated the effect of these conditions on the degradation of the microbial population. Ehara et al. [86] studied PE degradation by manganese peroxidase when hydrogen peroxide was in limited levels. Furthermore, Ray et al. [87] studied the biocatalytic oxidation of laccase to decrease the surface hydrophobicity of the plastic. This preliminary research can be used as an effective method to improve the biofilm-mediated degradation of PE and polycarbonate plastics.

7. Interaction of Polyethylene with Plants

The interactions of different types of PE are presented in Table 2. Different plants and crops were used in different types of soil. The results showed differences between the size of each PE, its concentration, and the period of the experiment.

The main effect on Chinese cabbage (*Brassica chinensis* L.) under the influence of HDPE MPs (48–150 µm) was a significantly reduced starch concentration in the leaves and leaf chlorophyll [88]. On the other side, phosphorus (P) and potassium (K) in the agricultural top soil (after specific processing) were decreased, and pH was increased [88]. A second study [89], using sandy soil (with/without earthworms) and LDPE MPs (50 µm–1 mm), also observed alterations in wheat (*Triticum aestivum*) plants; specifically, the number of the fruits, the area and the amount of leaves, and the root biomass of the plant were decreased. However, a high relative chlorophyll value was measured [89]. Using HDPE MPs (0.48–316 µm), [70] also observed an increase in the root biomass of their plant, perennial ryegrass (*Lolium perenne*) with rosy-tipped earthworms (*Aporrectodea rosea*); the chlorophyll-a/chlorophyll-b ratio was increased too. In particular, another study [90], found that the length and area of the roots were increased while the average diameter was decreased using spring onions (*Allium fistulosum*) in loamy sandy soil. No effect on the root growth of spring barley (*Hordeum vulgare* L.), as well as shoot growth inhibition, was observed by Reay et al. [91] in sandy clay loam using HDPE (1 cm × 1 cm). Effects on the inhibition of growth of *Thinopyrum junceum* L. and *Carpobrotus* sp. were researched by a recent study [92] using macroplastic (25 cm × 25 cm) HDPE in fine sand.

Different research [16] showed that the form of LDPE (foams and films) can affect the plant wild carrot (*D. carota*) in dry sandy loam soil in different ways. Specifically, shoot mass increased by ~65% while most soil aggregation decreased by ~32%. Root mass increased by ~80% using the LDPE samples in a film shape. Microbial activity decreased both by foam and film LDPE [16]. In another study by Qi et al. [89], MPs and macroplastics of mulch films and also LDPE [1% (w/w)] were used for 2 months (Table 2). During both vegetative and reproductive growth, the wheat plant was impacted by both macro- and microplastic wastes in both the above-ground and below-ground sections. However, the earthworms improved the development of the wheat and mostly mitigated the damage caused by plastic waste [89].

Figure 7 provides the percentages of articles that refer to the parameters that determine the effects of plastics in soils on crop plants. As expected, the type of plant is the dominant parameter that modulates the uptake or even the translocation of plastic fragments within

the plant, either in the root system or in the above-ground part [30,37]. Also, in most papers, it seems that the size and the type of plastics affect their uptake by plant tissues. The statistically processed articles refer to agricultural soils, without references to the presence of plants grown in urban soils.

LDPE, HDPE, and high-molecular-weight high-density polyethylene (HMHDPE) strips (10 cm × 10 cm) in three different conditions, i.e., black soil, sandy soil and red soil, were examined by Konduri and Bogolu [93] for 3 months. The highest degradation of all the three types of strips was observed in black soil in relation to the other two soil types. In black soil, HDPE was found to be the most sensitive of all the plastic films, losing 33% of its weight and 34% of its elongation percentage, while LDPE lost 26% of its weight and 34% of its elongation percentage; HMHDPE was shown to be very resistant in all of the soils [93].

Enzymes that are capable breakoff breaking the polymer backbones of synthetic plastics use plant polymers as natural substrates. For instance, cutinase hydrolyzes cutin, an aliphatic polyester that is found in the cuticle of plants. Ester bonds in PET and PUR can also be hydrolyzed by these enzymes. Numerous enzymes involved in plant lignin metabolism are involved in the thermoplastic polyolefin PE degradation as well [94]. Polyolefins are a group of thermoplastics with mainly high chemical resistance (<https://sintac.es/en/polyolefins/>, accessed on 4 January 2024). According to Ojeda et al. [95], high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), and polypropylene (PP) are good examples of the polymers known as polyolefins, which are created by addition reactions of unsaturated monomers, or alkyl-ethylenes.

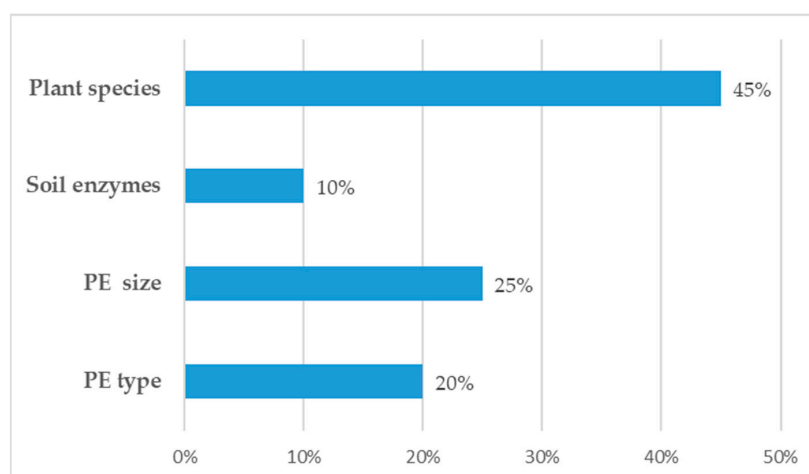


Figure 7. Percentages of articles on plant–microplastic relationships in agricultural soils.

Table 2. Summary table of the interaction of different plastic types of polyethylene (PE) with different soil conditions and plants/crops.

Type of PE	Description of the PE Sample	Characteristics of Soil	Type of Plant/Crop	Effects	References
HDPE	20 g kg ^{−1} Size: 48–150 µm	Pot experiment top soil (20 cm) of agricultural land in Changsha, China. It was air-dried. Stones, residues of plants, and animals were removed.	Chinese cabbage (<i>Brassica chinensis</i> L.)	Starch concentration in the leaves was significantly reduced.	[88]
				The concentration of leaf chlorophyll was consistently lowered by the addition of MPs at several application rates and sizes.	
				Phosphorus (P) and potassium (K) were decreased	
				Increase of pH	

Table 2. Cont.

Type of PE	Description of the PE Sample	Characteristics of Soil	Type of Plant/Crop	Effects	References
LDPE	1% (w/w) 50 µm–1 mm Exposure time: 2 months	Sandy soil (with/without earthworms)	Wheat (<i>Triticum aestivum</i>)	Fruit: the number of fruits was decreased Root: biomass was significantly decreased. Leaf: the numbers and area were decreased; higher relative chlorophyll value	[89]
HDPE	Size: 0.48–316 µm Mean diameter: 102.6 µm Clothing-fiber MPs	Mesocosm experiment using sandy clay	<i>Lolium perenne</i> (perennial ryegrass) with <i>Aporrectodea rosea</i> (rosy-tipped earthworm)	Root: the root biomass and the chlorophyll-a/chlorophyll-b ratio was increased. pH of the soil was decreased.	[70]
HDPE	2% (w/w) Average Diameter: 643 µm Exposure Time: 1.5 Months	Loamy sandy soil collected from Freie Universität Berlin	Spring onions (<i>Allium fistulosum</i>)	Root: the length and area were increased; the average diameter was decreased.	[90]
HDPE	Concentration: 0.2 g/kg Size: 2–5 mm Exposure Time: 5 m	Soil with microbiological activity. Clay pots under greenhouse conditions were used. Cadmium in the soil–plant system was tested.	Strawberry	HDPE affects plant height, stem thickness, biomass, root volume, and surface area. Mechanisms: The synthesis of chlorophyll and its stable binding with proteins is inhibited.	[96]
HDPE	Size: 1 cm × 1 cm 2% (w/w)	Glass Mesocosms experiment. Soil: from the top 10 cm of a grassland (<i>Lolium perenne</i> L.), Abergwyngregyn, Wales Structure: sandy clay loam and crumb.	Spring barley (<i>Hordeum vulgare</i> L.)	No effect on root growth and shoot growth inhibition.	[91]
HDPE	25 cm × 25 cm	Fine sand: dune system of Tuscany, Italy	<i>Thinopyrum junceum</i> L. and <i>Carpobrotus</i> sp.	Growth inhibition was observed	[92]
LDPE	Foams and Films	Dry sandy loam soil (0.07% N, 0.77% C, pH 6.66)	<i>D. carota</i> (wild carrot)	Foams: increased shoot mass ~65%. decreased the most soil aggregation (~32%) Films: increased root mass ~80% Foam and Film: decreased microbial activity	[16]

Table 2. Cont.

Type of PE	Description of the PE Sample	Characteristics of Soil	Type of Plant/Crop	Effects	References
LDPE	Macroplastics of mulch films: average length was 6.92 ± 1.47 mm and the average width was 6.10 ± 1.39 mm. MPs of mulch films: 12.5% of 1 mm to 500 μ m, 62.5% of 500 μ m to 250 μ m, and 25% of 250 μ m to 50 μ m. 2 months 1% (w/w)	Sandy soil	Wheat plant	During both vegetative and reproductive growth, the wheat plant was impacted by both macro- and microplastic wastes in both the above-ground and below-ground sections. The earthworms improved the development of the wheat and mostly mitigated the damage caused by plastic waste.	[89]
LDPE, HDPE and HMHDPE	Strips (10 cm $\times$ 10 cm)	Different soil conditions: black soil, sandy soil, and red soil. Placed 10 cm from the ground level for 3 months.		Higher degradation of PE films in black soil was observed than in the other two soil types. In black soil, HDPE was found to be the most sensitive of all the plastic films, losing 33% of its weight and 34% of its elongation percentage, while LDPE lost 26% of its weight and 34% of its elongation percentage. With no important weight loss and a 15% elongation percentage, HMHDPE was shown to be very resistant in all of the soils.	[93]

8. Interaction of Polyethylene with Soil Microbes

Biodegradation processes by soil microorganisms were shown by studies (Table 3), using different shapes and sizes of LDPE. Microorganisms secrete a variety of enzymes into the media, which begins the breakdown of the polymers, as found by Hussein et al. [97] using *Pseudomonas fluorescens*, *Pseudomonas aeruginosa*, and *Acinetobacter ursingii*; they also observed their potential ability to grow on LDPE powder while choosing to grow on LDPE strip as a sole source of carbon. In addition, out of ten efficient strip-degrading bacteria, three isolates appeared to decrease in pH medium [97]. By selecting the soil fungus *Aspergillus clavatus*, Gajendiran et al. [98] measured the degradation of 20 μ m thick LDPE strips as well as CO₂ evolution, morphological changes, and weight loss of LDPE.

UV-irradiated and non-UV-irradiated LDPE films (20 mm thick) had corresponding percentages of biodegradation at 29.5% and 15.8%, respectively [99]. Biodegradation was significantly more effective when the chosen microorganisms (mixed culture) were present in landfill soils [99]. Another study [38] used an antibiotic contaminant (ciprofloxacin) in combination with 1% (w/w) PE MPs (unknown type) and various types of microorganisms (Table 3) in soil medium, concluding that *Serratia* and *Achromobacter* were abundant in the polluted soil.

Figure 8 compares the percentages of published articles on the factors affecting the relationships between plastics and microbiota in agricultural soils. It is obvious that in most of the articles (50%), it is mentioned that the type of microorganism contributes to the interactive relationship with microplastics. The Figure refers to articles that analyzed agricultural soils.

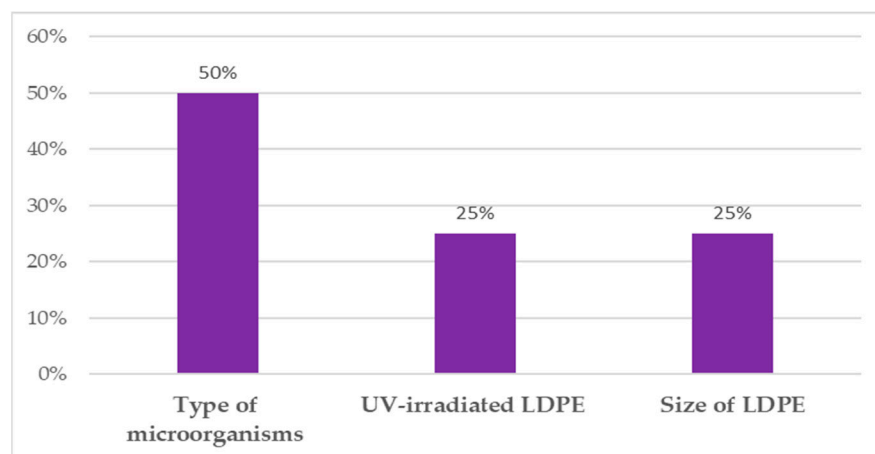


Figure 8. Presentation of the percentages of published articles referring to the parameters that differentiate and determine the relationship between plastics (MPPEs) and soil microbes in agricultural soils.

Biodegradation

All living cells, and therefore all microbes, contain enzymes. Because enzymes have very specific actions on substrates, different types of plastics can be degraded by different enzymes [100]. The actinomycete *R. ruber* produces laccase, which aids in the biodegradation of polyethylene. The majority of lignin-biodegrading fungi contains laccases, which catalyse the oxidation of aromatic compounds [101]. The oxidation of polyethylene's hydrocarbon backbone can be aided by laccase. Cell-free laccase incubated with polyethylene reduces the average molecular weight and average molecular number of polyethylene by 20 and 15%, respectively, according to gel permeation chromatography [102].

Most plastics made from petroleum are semi-crystalline, i.e., they have crystalline and amorphous regions. The amorphous regions can be more susceptible to microorganisms' influence than the crystalline parts. However, following the complete consumption of the amorphous parts, a thermally pretreated PE sample's crystalline fraction was degraded. It has been demonstrated that a fungal polyester hydrolase completely breaks down low-crystallinity PET films at a nearly linear rate, suggesting that the enzyme also targets the crystalline portions of the films [94,96].

Table 3. Summary table of the interaction of different plastic types of polyethylene (PE) with soil, plants, microorganisms, and different pollutants.

Characteristics of the Plastic	Description of the PE Sample	Information About Soil, Plant or Microorganisms	Type of Pollutant	Effects	References
HDPE	Concentration: 0.2 g/kg Size: 2–5 mm Exposure Time: 5 m Black in color; 20 µm thick; Carbon black + uv additive.	Strawberry plants (<i>Fragaria × ananassa</i> Duch) were used.		HDPE and HDPE + Cd affect plant height, stem thickness, biomass, root volume, and surface area.	[96]
		Soil–sand; 1:1 = Vol:Vol.		Cd ($Cd > 3 \text{ mg kg}^{-1}$) + HDPE: the total number of fruits and biomass per plant were decreased.	
		Soil with microbiological activity.	Cd	Mechanisms: The synthesis of chlorophyll and its stable binding with proteins was inhibited.	
		Clay pots under greenhouse conditions were used.	Cd + MPs		
		Period: August 2020 to February 2021.		A positive correlation between Cd and microbial biomass.	

Table 3. Cont.

Characteristics of the Plastic	Description of the PE Sample	Information About Soil, Plant or Microorganisms	Type of Pollutant	Effects	References
LDPE	Films (black, normal, thermic, and extra-low density)	agricultural soil	Organochlorine and organophosphorus pesticides	Pesticides' chemical structure had little effect on the plastic film's absorption process. All of the pesticides on the plastic films were absorbed. Pesticides continued to contaminate the plastic film (great stability)	[103]
PE	Plastic powders (size: 120 µm and 180 µm) Plastic pellets (size: 2000 µm and 3000 µm)	Soil suspension (The tested soil was air-dried and passed through a 200-mesh sieve.)	Organochlorine pesticides (OCPs): hexachlorocyclohexanes (HCHs) and dichlorodiphenyl-trichloroethanes (DDTs)	The sorption equilibrium was 12 h When the ratio of solution to soil was between 75:1 and 100:1, the MPs exhibited a good sorption effect on OCPs. The sorption capacity of MPs reduces, with increasing diameter.	[104]
PE	2.5% and 5% (<i>w/w</i>) Microplastic fragments (<5 mm)	Agricultural soil Urban soil Leafy vegetables	Zn and Cd	Higher metal accumulation in lettuce roots than in the edible above-ground parts of the plants.	[13]
HDPE	Four groups with different particle sizes: 48–58 µm, 100–154 µm, 0.6–1.0 mm, and 1.0–2.0 mm 0.01%, 0.1%, 1%, and 10% (<i>w/w</i>) Degree of crystallinity about 80–90%	Farmland soil (alfisols) Texture: Sandy loam Climate: maritime monsoon	Cd (adsorption and desorption)	Cd adsorption in the soil was reduced by adding MPs, while Cd desorption was enhanced. In the first ten minutes, over 98% of the total Cd was adsorbed due to the rapid process. Addition of MPs decreased the amount of Cd that could be retained in the soil and increased its mobility.	[1]
PE	MPs (10%) Two average sizes: 129 µm and 293 µm.	Top soil (0–20 cm) in the Northeast Forestry University campus.	Zn ²⁺ and Pb ²⁺ (adsorption–desorption behavior)	Decreased adsorption capability of metals to soil. Increased desorption percentage from soil. Increased bioavailability of metals in soil.	[105]

Table 3. Cont.

Characteristics of the Plastic	Description of the PE Sample	Information About Soil, Plant or Microorganisms	Type of Pollutant	Effects	References
PE	MPs 1% (w/w)	Top soil (0–30 cm), Tianjin University, northern China. Proteobacteria, Actinobacteria, and Chloroflexi (phylum level) and <i>Arthrobacter</i> (genus level) were included.	Ciprofloxacin (antibiotic contamination) 10 mg/kg	<i>Serratia</i> and <i>Achromobacter</i> were abundant in the polluted soil.	[38]
LDPE	Powder 0.1% (wt/v) and plastic bag strips (5 cm × 1 cm)	Samples from different municipal landfill regions in Baghdad city [superficial layer of soil (5–10 cm) in depth]. <i>Pseudomonas fluorescens</i> , <i>Pseudomonas aeruginosa</i> , and <i>Acinetobacter ursingii</i> were used.		Potential ability to grow on LDPE powder and chose to grow on LDPE strip as a sole source of carbon. High efficiency in degrading LDPE. From ten efficient strip-degrading bacteria, three isolates appeared to decrease in pH medium.	[97]
LDPE	Films (20 mm thick) and powder (0.1%)	Landfill soils, Tehran Mixed culture of <i>Lysinibacillus xylanilyticus</i> and <i>Aspergillus niger</i> .		Biodegradation was significantly more effective when the chosen microorganisms were present (the UV-irradiated and non-UV-irradiated films had corresponding percentages of biodegradation at 29.5% and 15.8%, respectively).	[99]
LDPE	20 µm thick strips	90 days of incubation in aqueous medium using soil fungus <i>Aspergillus clavatus</i>		Degradation of the plastic was observed: CO ₂ evolution, morphological changes, and weight loss of LDPE.	[98]

9. Interaction of Polyethylene with Organic and Inorganic Pollutants

There are different factors that affect the sorption of organic pollutants on plastics, such as their properties like functional groups, particle sizes, crystallinity, charging conditions, and environmental factors, such as salinity, pH, temperature, and dissolved organic matter (DOM) [106].

As mention previously, there are crystalline and amorphous zones in plastic polymers [e.g., 50–60% for LDPE with density 0.92 g·cm^{−3} and 70–95% for HDPE with density 0.93–0.97 g·cm^{−3}] [106]. In comparison to crystalline areas, amorphous regions of MPs have larger free volumes and a higher attraction for organic contaminants. An increase in MP crystallinity leads to a decrease in pollutant adsorption amount and adsorption rate. For instance, a typical low-crystallinity PE has stronger adsorption effect than other polymers like PS [106].

The specific surface area and adsorption capacity of MPs increase with decreasing particle size [106]. According to Hüffer et al. [107], the transport of organic contaminants in soil is influenced by PE MPs; organic pollutants in soil may become more mobile due to PE pollution, which would lower the soil's inherent ability for retention. This raises the possibility that organic pollutants will eventually find their way into groundwater, posing an even greater threat to public health [107].

Figure 9 presents the percentages of published gels that refer to the microplastic characteristics of the two types of polyethylene, both in urban and rural soils. The type of pollutant associated with plastics in soils is more important in urban soils (50%) and less important in rural soils (35%), based on all the published papers of the researchers.

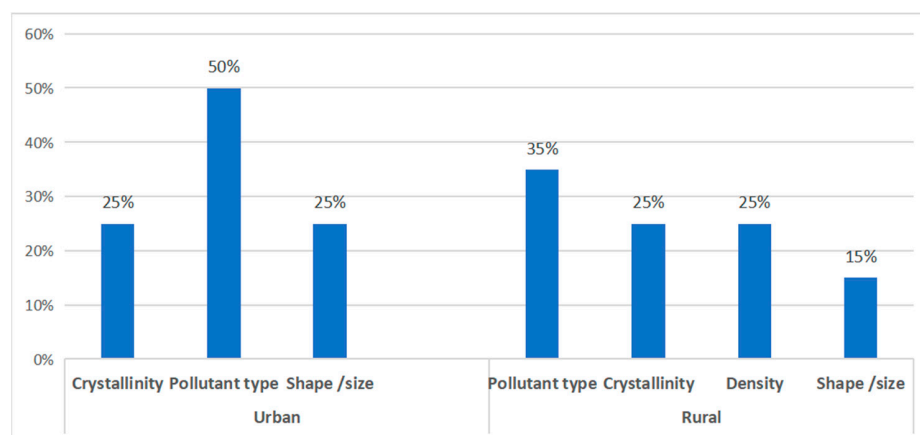


Figure 9. The percentage of published articles presenting the factors determining the effect of the two types of PE with organic and inorganic pollutants on urban and rural soils.

A wide range of reactions can arise between the metals contained in soils and MPs [59]. This fact has triggered a great deal of research on MPs and the inorganic and organic pollutants coexisting in soils. Lozano et al. [16] concluded that the shape, the type, and the plastic concentration can affect soil properties. Furthermore, De Souza Machado and his colleagues [90] also indicated that almost all types of MPs can change soil properties and affect plant performance. The researchers Huang et al. [108], in their meta-analysis, concluded that different types of MPs can induce environmental risks as they can enhance Cd uptake by plants. Different types of MP polymers can significantly increase the accumulation of toxic metals in plants, while PE seems to have a greater and more significant effect. Khalid et al. [109] also indicated that MPs could be a threat to plants directly or indirectly. This is mainly explained by the fact that PEs usually induce alterations to soil physicochemical properties, such as a decrease in soil reaction, followed by an increase in the bioavailability of metals. Feng et al. [110], in their investigation, found that MPs can significantly change soil physicochemical properties and thus can alter heavy metal mobility. In addition, Wen et al. [111], in their investigation, found that MPs can affect the chemical speciation of metals in the soil system, inducing chemical reactions in biota. The uptake and the tracing of PE MPs in crop plants using lanthanide chelates as a dual-functional tracer has been examined by Luo et al. [112]. Furthermore, Shi et al. [113] investigated the impact of PE on soil physicochemical properties and characteristics of sweet potato growth.

However, any changes occurring in soil properties and in the availability of non-metallic and metallic nutrients are not constant, as they depend on a number of factors, whose control is not completely feasible nor are their mechanisms of action fully understood. Therefore, while a large number of studies have led to the conclusion that the addition of MPs and PE in particular leads to a decrease in soil pH, the researchers Wang et al. [114] have indicated that PE MPs cause an increase in cadmium uptake by lettuce plants by altering the soil microenvironment.

Admittedly, it is conceivable that different conclusions can be reached if experiments are carried out in pots versus in the field. It is well understood that plants are stressed

in a different way, yet the incubation conditions of the MPs are also dissimilar when experiments are conducted in pots. On the other hand, the influence of continuous and long-term exposure to solar radiation and increased temperature is quite different in the field, especially in warm climates, as is usually seen in Mediterranean countries. In their research, Zhao et al. [115] found that typical MPs in field and facility agriculture alter the available Cd concentrations in different soil types, as they eventually change the physicochemical dynamics of soil organic carbon, available Fe, and soil microbes.

Nutritional elements are affected in various ways by the presence of MPs, as elaborated on in the research by Liu et al. [116], in which they studied the effect of MPs on both soils and wheat crops. They observed that under the specific conditions of the experiment, the increase in nutrient uptake could be significant and potentially lead to sustainable development solutions for intensively cultivated agricultural land. Furthermore, Tang et al. [117] investigated the effects of MPs on the absorption and accumulation of elements in hydroponic rice seedlings (*Oryza sativa* L.), pointing out that these physicochemical processes may determine the amount of elements that can be absorbed by rice. However, together with nutrients and toxic elements, such as Cd, it is naturally possible to be taken up by plants, and their coexistence with MPs may have a synergistic or antagonistic effect, according to the work of Wang et al. [38] regarding the effects of co-contamination of MPs and Cd on plant growth along with Cd accumulation. Although Yu et al. [28] investigated the bioavailability decrease in soil heavy metals caused by the presence of MPs, Bethanis and Golia [13] demonstrated that by adding two different levels of PE to soil samples from Mediterranean soils, there is a decrease in pH and an increase in the available concentration of Zn and Cd, with the increase in the most toxic element being smaller, related to the increase in the available concentration of Zn.

The impact of MPs on the nitrogen cycle is perhaps the most important impact of plastics on the soil system. Bethanis and Golia [23] studied the implications for nitrogen (N) cycling along with soil microbial activity, as they completed a study regarding the unraveling consequences of soil micro- and nano-plastic pollution on soil–plant systems in a wide range of soil types.

The researchers Gao et al. [118] investigated the effect of PE particles on dibutyl phthalate toxicity in lettuce, confirming the strong interaction that the organic molecules present in soils can have with the inorganic molecules that in any case make up plastics. Furthermore, Liu et al. [119] confirmed the joint toxicity of PE MPs and phenanthrene to wheat seedlings, which can have significant effects on wheat production but also on crop yield in general.

Sorption and desorption behavior can be examined in plastics using pollutants (Table 3). Using Zn^{2+} and Pb^{2+} in top soil (0–20 cm) and PE MPs at 129 μm and 293 μm (10%) a decreased adsorption capability of metals to soil and an increase in the desorption percentage from soil were observed [105]; another main conclusion by the same research is that the bioavailability of metals in soil was increased. Sorption and desorption experiments were conducted by Zhang et al. [1], who also observed the adsorption type of sorption. Four groups with different particle sizes of HDPE in alfisol soil were used. Cd adsorption in the soil was reduced by adding MPs, while Cd desorption was enhanced. In the first ten minutes, over 98% of the total Cd was adsorbed due to the rapid process, while the addition of MPs decreased the amount of Cd that could be retained in the soil and increased its mobility [1]. A higher metal accumulation (Zn and Cd) in the roots of leafy vegetables was observed than in the edible above-ground parts of the plants, as found by Bethanis and Golia [13] using PE fragments (<5 mm) at 2.5% and 5% (*w/w*) in urban and agricultural soils. A heavy metal Cd was also examined by Pinto-Poblete et al. [96], who used HDPE with a black color (Table 3) due to additives. They used oil with microbiological activity and strawberry plants in two combinations: Cd and Cd + MPs. The main effects were [96] A) HDPE and HDPE + Cd affected plant height, stem thickness, biomass, root volume, and surface area; additionally, the synthesis of chlorophyll and its stable binding with proteins were inhibited; B) Cd + HDPE: the total number of fruits and biomass per plant

decreased when $Cd > 3 \text{ mg kg}^{-1}$; and C) there was a positive correlation between Cd and microbial biomass.

Different groups of pollutants (pesticides: organochlorine and organophosphorus pesticides) were examined by Nerín et al. [103], using LDPE films, i.e., black, normal, thermic, and extra-low density in agricultural soil. All of the pesticides on the plastic films were sorbed (absorption process), while the pesticides' chemical structures had little effect on the plastic film's absorption process, continuing to contaminate the plastic film (great stability). Based on another experiment using soil suspension and PE (powder and pellets), the MPs exhibited a good sorption effect on organochlorine pesticides (the sorption equilibrium was 12 h) when the ratio of solution to soil was between 75:1 and 100:1 [104].

Numerous approaches have been proposed to eliminate a range of pollutants from soils. The method of phytoremediation is of paramount importance, as it is economical and eco-friendly [120].

10. Conclusions

Based on the current comprehensive review, several conclusions can be captured. Rural and urban soils interact dynamically with other environments like the atmosphere and aquatic mediums, and this affects (micro)plastic chemical alteration and transportation. There are different subcategories of soil types in rural and urban areas, and they are sources for different types of plastic litter and other pollutants (organic or inorganic). As a significant common type of plastic, PE's 'behavior' in soil varies according to its density, branching, crystallinity, and relative molecular mass; for instance, LDPE and HDPE, types of polyethylene with different crystallinities and densities, present different interactions in soil. In general, interactions of PE depend on its classifications and type (e.g., size), vegetation, soil type, and microbial load, as well as physical parameters such as the weather conditions. The current investigation provides a novel perspective in understanding the mechanisms that unfold between polyethylene microplastics and soil system components. Upon entry, microplastics are able to modulate the physicochemical properties of soils, causing chain reactions in the availability of nutrients as well as toxic elements, both inorganic and organic, existing in the soil. Therefore, perhaps the presence of PE microplastics (LDPE and HDPE) can contribute to the sustainability of urban and rural soils with proper management.

11. Perspectives

According to this study, some suggestions can be written:

- To obtain a clear picture of the impact of plastics on the soil, including their impacts on plants, extensive sampling is required, for instance, measuring and correlating different parameters of the roots of plants.
- Study of the effects of plastics on agricultural land, due to their on-site burning, is recommended.
- The current overview presented differences between the different types of PE. Specifically, the LDPE and HDPE types were mainly selected by the scientific literature, while a relatively high number of publications referred to the general use of the term PE. We would recommend that in further studies, the various forms of polyethylene should be analyzed separately.
- Even though Zettler et al. [121] have studied plastics in the marine environment, it is important that their proposals also refer to the soil environment; that the directions of their research contain an understanding of the genetic mechanisms by which microorganisms attach to soil plastic debris (SPL); and that they clarify the microorganisms/genes involved in the microbial-mediated degradation of plastics through the study of large-scale culture collections.
- The biodegradation processes of less-studied soil microorganisms, in combination with other techniques (e.g., for reducing crystallinity artificially), would lead to an

application for the processing of non-recyclable plastics as well as the possible remediation of the environment from plastics.

- In some scientific articles, LDPE is referred as Light-Density PE rather than low-density PE; we mention it as minor comment.
- Additionally, we suggest a scientific investigation on the effects of plastics from party events on the environment.

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References

1. Zhang, S.; Han, B.; Sun, Y.; Wang, F. Microplastics Influence the Adsorption and Desorption Characteristics of Cd in an Agricultural Soil. *J. Hazard. Mater.* **2020**, *388*, 121775. [\[CrossRef\]](#)
2. Kumar, R.; Manna, C.; Padha, S.; Verma, A.; Sharma, P.; Dhar, A.; Ghosh, A.; Bhattacharya, P. Micro(Nano)Plastics Pollution and Human Health: How Plastics Can Induce Carcinogenesis to Humans? *Chemosphere* **2022**, *298*, 134267. [\[CrossRef\]](#)
3. Kye, H.; Kim, J.; Ju, S.; Lee, J.; Lim, C.; Yoon, Y. Microplastics in Water Systems: A Review of Their Impacts on the Environment and Their Potential Hazards. *Heliyon* **2023**, *9*, e14359. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Sa'adu, I.; Farsang, A. Plastic Contamination in Agricultural Soils: A Review. *Environ. Sci. Eur.* **2023**, *35*, 13. [\[CrossRef\]](#)
5. Stefánsson, H.; Peternell, M.; Konrad-Schmolke, M.; Hannesdóttir, H.; Ásbjörnsson, E.J.; Sturkell, E. Microplastics in Glaciers: First Results from the Vatnajökull Ice Cap. *Sustainability* **2021**, *13*, 4183. [\[CrossRef\]](#)
6. Zalasiewicz, J.; Waters, C.N.; Ivar do Sul, J.A.; Corcoran, P.L.; Barnosky, A.D.; Cearreta, A.; Edgeworth, M.; Gałuszka, A.; Jeandel, C.; Leinfelder, R.; et al. The Geological Cycle of Plastics and Their Use as a Stratigraphic Indicator of the Anthropocene. *Anthropocene* **2016**, *13*, 4–17. [\[CrossRef\]](#)
7. Crawford, C.B.; Quinn, B. *Microplastic Pollutants*; Elsevier: Amsterdam, The Netherlands, 2016.
8. Chiba, S.; Saito, H.; Fletcher, R.; Yogi, T.; Kayo, M.; Miyagi, S.; Ogido, M.; Fujikura, K. Human Footprint in the Abyss: 30 Year Records of Deep-Sea Plastic Debris. *Mar. Policy* **2018**, *96*, 204–212. [\[CrossRef\]](#)
9. Bockheim, J.G.; Gennadiyev, A.N. Soil-Factorial Models and Earth-System Science: A Review. *Geoderma* **2010**, *159*, 243–251. [\[CrossRef\]](#)
10. Su, L.; Xiong, X.; Zhang, Y.; Wu, C.; Xu, X.; Sun, C.; Shi, H. Global Transportation of Plastics and Microplastics: A Critical Review of Pathways and Influences. *Sci. Total Environ.* **2022**, *831*, 154884. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Allen, S.; Allen, D.; Phoenix, V.R.; Le Roux, G.; Durántez Jiménez, P.; Simonneau, A.; Binet, S.; Galop, D. Atmospheric Transport and Deposition of Microplastics in a Remote Mountain Catchment. *Nat. Geosci.* **2019**, *12*, 339–344. [\[CrossRef\]](#)
12. Tziourrou, P.; Megalovasilis, P.; Tsounia, M.; Karapanagioti, H.K. Characteristics of Microplastics on Two Beaches Affected by Different Land Uses in Salamina Island in Saronikos Gulf, East Mediterranean. *Mar. Pollut. Bull.* **2019**, *149*, 110531. [\[CrossRef\]](#)
13. Bethanis, J.; Golia, E.E. Revealing the Combined Effects of Microplastics, Zn, and Cd on Soil Properties and Metal Accumulation by Leafy Vegetables: A Preliminary Investigation by a Laboratory Experiment. *Soil Syst.* **2023**, *7*, 65. [\[CrossRef\]](#)
14. Rummel, C.D.; Jahnke, A.; Gorokhova, E.; Kühnel, D.; Schmitt-Jansen, M. Impacts of Biofilm Formation on the Fate and Potential Effects of Microplastic in the Aquatic Environment. *Environ. Sci. Technol. Lett.* **2017**, *4*, 258–267. [\[CrossRef\]](#)
15. Yue, Y.; Li, X.; Wei, Z.; Zhang, T.; Wang, H.; Huang, X.; Tang, S. Recent Advances on Multilevel Effects of Micro(Nano)Plastics and Coexisting Pollutants on Terrestrial Soil-Plants System. *Sustainability* **2023**, *15*, 4504. [\[CrossRef\]](#)
16. Lozano, Y.M.; Lehnert, T.; Linck, L.T.; Lehmann, A.; Rillig, M.C. Microplastic Shape, Polymer Type, and Concentration Affect Soil Properties and Plant Biomass. *Front. Plant. Sci.* **2021**, *12*, 616645. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Zheng, S.; Bawazir, M.; Dhall, A.; Kim, H.-E.; He, L.; Heo, J.; Hwang, G. Implication of Surface Properties, Bacterial Motility, and Hydrodynamic Conditions on Bacterial Surface Sensing and Their Initial Adhesion. *Front. Bioeng. Biotechnol.* **2021**, *9*, 643722. [\[CrossRef\]](#) [\[PubMed\]](#)

18. Wiesinger, H.; Wang, Z.; Hellweg, S. Deep Dive into Plastic Monomers, Additives, and Processing Aids. *Environ. Sci. Technol.* **2021**, *55*, 9339–9351. [[CrossRef](#)] [[PubMed](#)]
19. Viera, J.S.C.; Marques, M.R.C.; Nazareth, M.C.; Jimenez, P.C.; Sanz-Lázaro, C.; Castro, Í.B. Are Biodegradable Plastics an Environmental Rip Off? *J. Hazard. Mater.* **2021**, *416*, 125957. [[CrossRef](#)] [[PubMed](#)]
20. Meijer, L.J.J.; van Emmerik, T.; van der Ent, R.; Schmidt, C.; Lebreton, L. More than 1000 Rivers Account for 80% of Global Riverine Plastic Emissions into the Ocean. *Sci. Adv.* **2021**, *7*, eaaz5803. [[CrossRef](#)]
21. Nizzetto, L.; Futter, M.; Langaas, S. Are Agricultural Soils Dumps for Microplastics of Urban Origin? *Environ. Sci. Technol.* **2016**, *50*, 10777–10779. [[CrossRef](#)]
22. He, D.; Luo, Y.; Lu, S.; Liu, M.; Song, Y.; Lei, L. Microplastics in Soils: Analytical Methods, Pollution Characteristics and Ecological Risks. *TrAC-Trends Anal. Chem.* **2018**, *109*, 163–172. [[CrossRef](#)]
23. Bethanis, J.; Golia, E.E. Micro- and Nano-Plastics in Agricultural Soils: A Critical Meta-Analysis of Their Impact on Plant Growth, Nutrition, Metal Accumulation in Plant Tissues and Crop Yield. *Appl. Soil Ecol.* **2024**, *194*, 105202. [[CrossRef](#)]
24. Möhrke, A.C.F.; Haegerbaeumer, A.; Traunspurger, W.; Höss, S. Underestimated and Ignored? The Impacts of Microplastic on Soil Invertebrates—Current Scientific Knowledge and Research Needs. *Front. Environ. Sci.* **2022**, *10*, 975904. [[CrossRef](#)]
25. Reynolds, J.F.; Mark, D.; Smith, S.; Lambin, E.F.; Turner, B.L., II; Mortimore, M.; Batterbury, S.P.J.; Downing, T.E.; Dowlatabadi, H.; Fernández, R.J.; et al. Global Desertification: Building a Science for Dryland Development. *Science* **2007**, *316*, 847–851. [[CrossRef](#)] [[PubMed](#)]
26. ISO/DIS 11466; Environment Soil Quality. ISO Standards Compendium: Zurich, Switzerland, 1994.
27. Golia, E.E.; Kantzou, O.-D.; Chartodiplomenou, M.-A.; Papadimou, S.G.; Tsiropoulos, N.G. Study of Potentially Toxic Metal Adsorption in a Polluted Acid and Alkaline Soil: Influence of Soil Properties and Levels of Metal Concentration. *Soil Syst* **2023**, *7*, 16. [[CrossRef](#)]
28. Yu, H.; Hou, J.; Dang, Q.; Cui, D.; Xi, B.; Tan, W. Decrease in Bioavailability of Soil Heavy Metals Caused by the Presence of Microplastics Varies across Aggregate Levels. *J. Hazard. Mater.* **2020**, *395*, 122690. [[CrossRef](#)] [[PubMed](#)]
29. Golia, E.E. The Impact of Heavy Metal Contamination on Soil Quality and Plant Nutrition. Sustainable Management of Moderate Contaminated Agricultural and Urban Soils, Using Low Cost Materials and Promoting Circular Economy. *Sustain. Chem. Pharm.* **2023**, *33*, 101046. [[CrossRef](#)]
30. Campanale, C.; Galafassi, S.; Savino, I.; Massarelli, C.; Ancona, V.; Volta, P.; Uricchio, V.F. Microplastics Pollution in the Terrestrial Environments: Poorly Known Diffuse Sources and Implications for Plants. *Sci. Total. Environ.* **2022**, *805*, 150431. [[CrossRef](#)] [[PubMed](#)]
31. Hodson, M.E.; Duffus-Hodson, C.A.; Clark, A.; Prendergast-Miller, M.T.; Thorpe, K.L. Plastic Bag Derived-Microplastics as a Vector for Metal Exposure in Terrestrial Invertebrates. *Environ. Sci. Technol.* **2017**, *51*, 4714–4721. [[CrossRef](#)] [[PubMed](#)]
32. Wu, S.; Xia, X.; Lin, C.; Chen, X.; Zhou, C. Levels of Arsenic and Heavy Metals in the Rural Soils of Beijing and Their Changes over the Last Two Decades (1985–2008). *J. Hazard. Mater.* **2010**, *179*, 860–868. [[CrossRef](#)]
33. Huang, M.; Zhou, S.; Sun, B.; Zhao, Q. Heavy Metals in Wheat Grain: Assessment of Potential Health Risk for Inhabitants in Kunshan, China. *Sci. Total. Environ.* **2008**, *405*, 54–61. [[CrossRef](#)] [[PubMed](#)]
34. Hofmann, T.; Ghoshal, S.; Tufenkji, N.; Adamowski, J.F.; Bayen, S.; Chen, Q.; Demokritou, P.; Flury, M.; Hüffer, T.; Ivleva, N.P.; et al. Plastics Can Be Used More Sustainably in Agriculture. *Commun. Earth Environ.* **2023**, *4*, 332. [[CrossRef](#)]
35. Kasirajan, S.; Ngouajio, M. Polyethylene and Biodegradable Mulches for Agricultural Applications: A Review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [[CrossRef](#)]
36. Monkul, M.M.; Özhan, H.O. Microplastic Contamination in Soils: A Review from Geotechnical Engineering View. *Polymers* **2021**, *13*, 4129. [[CrossRef](#)] [[PubMed](#)]
37. Edo, C.; González-Pleiter, M.; Leganés, F.; Fernández-Piñas, F.; Rosal, R. Fate of Microplastics in Wastewater Treatment Plants and Their Environmental Dispersion with Effluent and Sludge. *Environ. Pollut.* **2020**, *259*, 113837. [[CrossRef](#)]
38. Wang, J.; Liu, X.; Dai, Y.; Ren, J.; Li, Y.; Wang, X.; Zhang, P.; Peng, C. Effects of Co-Loading of Polyethylene Microplastics and Ciprofloxacin on the Antibiotic Degradation Efficiency and Microbial Community Structure in Soil. *Sci. Total. Environ.* **2020**, *741*, 140463. [[CrossRef](#)]
39. Syranidou, E.; Kalogerakis, N. Interactions of Microplastics, Antibiotics and Antibiotic Resistant Genes within WWTPs. *Sci. Total. Environ.* **2022**, *804*, 150141. [[CrossRef](#)]
40. Österlund, H.; Blecken, G.; Lange, K.; Marsalek, J.; Gopinath, K.; Viklander, M. Microplastics in Urban Catchments: Review of Sources, Pathways, and Entry into Stormwater. *Sci. Total. Environ.* **2023**, *858*, 159781. [[CrossRef](#)]
41. De Falco, F.; Di Pace, E.; Cocca, M.; Avella, M. The Contribution of Washing Processes of Synthetic Clothes to Microplastic Pollution. *Sci. Rep.* **2019**, *9*, 6633. [[CrossRef](#)] [[PubMed](#)]
42. Sang, W.; Chen, Z.; Mei, L.; Hao, S.; Zhan, C.; Zhang, W.B.; Li, M.; Liu, J. The Abundance and Characteristics of Microplastics in Rainwater Pipelines in Wuhan, China. *Sci. Total. Environ.* **2021**, *755*, 142606. [[CrossRef](#)] [[PubMed](#)]
43. Manju, R.; Sathya, S.; Sheema, K. Use of Plastic Waste in Bituminous Pavement. *Int. J. ChemTech Res.* **2017**, *10*, 804–811.
44. Wang, B.; Li, Y.; Cai, X. The Implementation Effects of Different Plastic Bag Ban Policies in China: The Role of Consumers' Involvement. *Environ. Res. Commun.* **2023**, *5*, 041002. [[CrossRef](#)]
45. The World Counts. How Many Plastic Bags Are Used Each Year? 2023. Available online: <https://www.theworldcounts.com/challenges/planet-earth/waste/plastic-bags-used-per-year> (accessed on 15 February 2024).

46. Eberhard, F.S.; Bowtell, L.; Lenske, B.; Islam, M.M. Investigation of Gas Release from Recycled Plastic Shopping Bags during Melting at Low Temperatures. *Adv. Mater. Sci. Eng.* **2023**, *2023*, 2378231. [[CrossRef](#)]
47. Boonyuid, C.; Amin, S. Impacts of Low-Density Polyethylene (Plastic Shopping Bags) on Structural Performance and Permeability of HMA Mixtures. *Int. J. Pavement Eng. Asph. Technol.* **2021**, *22*, 35–55.
48. Rajendran, S.D.; Velu, R.K.; Krishnan, N.; Duraisamy, N.; Kanthaiah, K.; Sekar, C.; Arokiaswamy, R.A. The Role of Microbes in Plastic Degradation. In *Environmental Waste Management*; Chandra, R., Ed.; CRC: Boca Raton, FL, USA, 2015; pp. 341–370.
49. Peng, Y.; Wu, P.; Schartup, A.T.; Zhang, Y. Plastic Waste Release Caused by COVID-19 and Its Fate in the Global Ocean. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2111530118. [[CrossRef](#)] [[PubMed](#)]
50. Benson, N.U.; Bassey, D.E.; Palanisami, T. COVID Pollution: Impact of COVID-19 Pandemic on Global Plastic Waste Footprint. *Heliyon* **2021**, *7*, e06343. [[CrossRef](#)] [[PubMed](#)]
51. Hiemstra, A.-F.; Rambonnet, L.; Gravendeel, B.; Schilthuizen, M. The Effects of COVID-19 Litter on Animal Life. *Anim. Biol.* **2021**, *71*, 215–231. [[CrossRef](#)]
52. Kouvara, K.; Papatheodorou, G.; Kosmopoulou, A.; Giovos, I.; Charitou, A.; Filippides, A.; Kaberi, H.; Kalaitzi, L.; Kyrkitsos, F.; Koundouri, P.; et al. COVID-19-Related Litter Pollution on Greek Beaches and Nearshore Shallow Water Environments. *Mar. Pollut. Bull.* **2022**, *185*, 114250. [[CrossRef](#)] [[PubMed](#)]
53. Webb, J.; Rubio, J.L.; Fullen, M.A. Soil Quality and Policy. In *Urban Pollution: Science and Management*; Wiley: Hoboken, NJ, USA, 2018. [[CrossRef](#)]
54. Nhung, N.T.H.; Nguyen, X.-T.T.; Long, V.D.; Wei, Y.; Fujita, T. A Review of Soil Contaminated with Dioxins and Biodegradation Technologies: Current Status and Future Prospects. *Toxics* **2022**, *10*, 278. [[CrossRef](#)] [[PubMed](#)]
55. Rashid, A.; Schutte, B.J.; Ulery, A.; Deyholos, M.K.; Sanogo, S.; Lehnhoff, E.A.; Beck, L. Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health. *Agronomy* **2023**, *13*, 1521. [[CrossRef](#)]
56. Du, L.; Liu, W. Occurrence, Fate, and Ecotoxicity of Antibiotics in Agro-Ecosystems. A Review. *Agron. Sustain. Dev.* **2012**, *32*, 309–327. [[CrossRef](#)]
57. Sun, Y.; Duan, C.; Cao, N.; Li, X.; Li, X.; Chen, Y.; Huang, Y.; Wang, J. Effects of Microplastics on Soil Microbiome: The Impacts of Polymer Type, Shape, and Concentration. *Sci. Total. Environ.* **2021**, *806*, 150516. [[CrossRef](#)] [[PubMed](#)]
58. Sun, Y.; Duan, C.; Cao, N.; Ding, C.; Huang, Y.; Wang, J. Biodegradable and Conventional Microplastics Exhibit Distinct Microbiome, Functionality, and Metabolome Changes in Soil. *J. Hazard. Mater.* **2022**, *424*, 127282. [[CrossRef](#)] [[PubMed](#)]
59. Wang, Q.; Feng, X.; Liu, Y.; Cui, W.; Sun, Y.; Zhang, S.; Wang, F. Effects of Microplastics and Carbon Nanotubes on Soil Geochemical Properties and Bacterial Communities. *J. Hazard. Mater.* **2022**, *433*, 128826. [[CrossRef](#)] [[PubMed](#)]
60. Liu, S.; Huang, J.H.; Zhang, W.; Shi, L.X.; Yi, K.X.; Zhang, C.Y.; Pang, H.L.; Li, J.N.; Li, S.Z. Investigation of the Adsorption Behavior of Pb(II) onto Natural-Aged Microplastics as Affected by Salt Ions. *J. Hazard. Mater.* **2022**, *431*, 128643. [[CrossRef](#)] [[PubMed](#)]
61. Chen, C.; Pan, J.; Xiao, S.; Wang, J.; Gong, X.; Yin, G.; Hou, L.; Liu, M.; Zheng, Y. Microplastics Alter Nitrous Oxide Production and Pathways through Affecting Microbiome in Estuarine Sediments. *Water Res.* **2022**, *221*, 118733. [[CrossRef](#)]
62. Liu, S.; Niu, S.-H.; Xiang, L.; Liao, X.-D.; Xing, S.-C. Effects of the Oversized Microplastic Pollution Layer on Soil Aggregates and Organic Carbon at Different Soil Depths. *J. Hazard. Mater.* **2023**, *450*, 131014. [[CrossRef](#)]
63. Ng, E.L.; Lin, S.Y.; Dungan, A.M.; Colwell, J.M.; Ede, S.; Huerta Lwanga, E.; Meng, K.; Geissen, V.; Blackall, L.L.; Chen, D. Microplastic Pollution Alters Forest Soil Microbiome. *J. Hazard. Mater.* **2021**, *409*, 124606. [[CrossRef](#)]
64. Yuan, Y.; Zu, M.; Li, R.; Zuo, J.; Tao, J. Soil Properties, Microbial Diversity, and Changes in the Functionality of Saline-Alkali Soil Are Driven by Microplastics. *J. Hazard. Mater.* **2023**, *446*, 130712. [[CrossRef](#)]
65. Jie, C.; Jing-zhang, C.; Man-zhi, T.; Zi-tong, G. Soil Degradation: A Global Problem Endangering Sustainable Development. *J. Geogr. Sci.* **2002**, *12*, 243–252. [[CrossRef](#)]
66. Alloway, B.J. Chapter 15—Mercury. In *Heavy Metals in Soils Trace Metals and Metalloids in Soils and Their Bioavailability*; Environmental Pollution; Springer: Dordrecht, The Netherlands, 2013.
67. Kabata-Pendias, A. *Trace Elements in Soils and Plants*, 4th ed.; CRC: Boca Raton, FL, USA, 2010.
68. Sparks, D.L. *Environmental Soil Chemistry*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2003.
69. O'Sullivan, G.; Sandau, C. *Environmental Forensics for Persistent Organic Pollutants*; Elsevier: Amsterdam, The Netherlands, 2013.
70. Boots, B.; Russell, C.W.; Green, D.S. Effects of Microplastics in Soil Ecosystems: Above and below Ground. *Environ. Sci. Technol.* **2019**, *53*, 11496–11506. [[CrossRef](#)] [[PubMed](#)]
71. Hou, L.; Xi, J.; Chen, X.; Li, X.; Ma, W.; Lu, J.; Xu, J.; Lin, Y.B. Biodegradability and Ecological Impacts of Polyethylene-Based Mulching Film at Agricultural Environment. *J. Hazard. Mater.* **2019**, *378*, 120774. [[CrossRef](#)] [[PubMed](#)]
72. Fa, W.; Wang, J.; Ge, S.; Chao, C. Performance of Photo-Degradation and Thermo-Degradation of Polyethylene with Photo-Catalysts and Thermo-Oxidant Additives. *Polym. Bull.* **2020**, *77*, 1417–1432. [[CrossRef](#)]
73. Briassoulis, D.; Aristopoulou, A.; Bonora, M.; Verlodt, I. Degradation Characterisation of Agricultural Low-Density Polyethylene Films. *Biosyst. Eng.* **2004**, *88*, 131–143. [[CrossRef](#)]
74. Ghatge, S.; Yang, Y.; Ahn, J.-H.; Hur, H.-G. Biodegradation of Polyethylene: A Brief Review. *Appl. Biol. Chem.* **2020**, *63*, 27. [[CrossRef](#)]
75. Eubeler, J.P.; Bernhard, M.; Knepper, T.P. Environmental Biodegradation of Synthetic Polymers II. Biodegradation of Different Polymer Groups. *TrAC-Trends Anal. Chem.* **2010**, *29*, 84–100. [[CrossRef](#)]

76. Shelciya, S.; Glen Esmeralda, V.; Patterson, J. Preliminary Study on the Role of Mangroves in Entrapping Microplastics in Tuticorin Coast of Gulf of Mannar, Southeast Coast of India. *Arch. Environ. Contam. Toxicol.* **2023**, *85*, 25–33. [\[CrossRef\]](#)
77. Ding, L.; Mao, R.; Ma, S.; Guo, X.; Zhu, L. High Temperature Depended on the Ageing Mechanism of Microplastics under Different Environmental Conditions and Its Effect on the Distribution of Organic Pollutants. *Water Res.* **2020**, *174*, 115634. [\[CrossRef\]](#)
78. Zhang, H.; Huang, Y.; Shen, J.; Xu, F.; Hou, H.; Xie, C.; Wang, B.; An, S. Mechanism of Polyethylene and Biodegradable Microplastic Aging Effects on Soil Organic Carbon Fractions in Different Land-Use Types. *Sci. Total. Environ.* **2024**, *912*, 168961. [\[CrossRef\]](#)
79. Tiwari, N.; Santhiya, D.; Sharma, J.G. Significance of Landfill Microbial Communities in Biodegradation of Polyethylene and Nylon 6,6 Microplastics. *J. Hazard. Mater.* **2024**, *462*, 132786. [\[CrossRef\]](#)
80. Orhan, Y.; Büyükgüngör, H. Enhancement of Biodegradability of Disposable Polyethylene in Controlled Biological Soil. *Int. Biodeterior. Biodegrad.* **2000**, *45*, 49–55. [\[CrossRef\]](#)
81. Bonhomme, S.; Cuet, A.; Delort, A.-M.; Lemaire, J.; Sancelme, M.; Scott, G. Environmental Biodegradation of Polyethylene. *Polym. Degrad. Stab.* **2003**, *81*, 441–452. [\[CrossRef\]](#)
82. Cai, L.; Wang, J.; Peng, J.; Wu, Z.; Tan, X. Observation of the Degradation of Three Types of Plastic Pellets Exposed to UV Irradiation in Three Different Environments. *Sci. Total. Environ.* **2018**, *628–629*, 740–747. [\[CrossRef\]](#)
83. Balasubramanian, V.; Natarajan, K.; Rajeshkannan, V.; Perumal, P. Enhancement of in Vitro High-Density Polyethylene (HDPE) Degradation by Physical, Chemical, and Biological Treatments. *Environ. Sci. Pollut. Res.* **2014**, *21*, 12549–12562. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Książek, E. Citric Acid: Properties, Microbial Production, and Applications in Industries. *Molecules* **2023**, *29*, 22. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Danso, D.; Chow, J.; Streit, W.R. Plastics: Environmental and Biotechnological Perspectives on Microbial Degradation. *Appl. Environ. Microbiol.* **2019**, *85*, 19. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Ehara, K.; Iiyoshi, Y.; Tsutsumi, Y.; Nishida, T. Polyethylene Degradation by Manganese Peroxidase in the Absence of Hydrogen Peroxide. *J. Wood Sci.* **2000**, *46*, 180–183. [\[CrossRef\]](#)
87. Ray, A.S.; Rajasekaran, M.; Uddin, M.; Kandasamy, R. Laccase Driven Biocatalytic Oxidation to Reduce Polymeric Surface Hydrophobicity: An Effective Pre-Treatment Strategy to Enhance Biofilm Mediated Degradation of Polyethylene and Polycarbonate Plastics. *Sci. Total. Environ.* **2023**, *904*, 166721. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Yang, M.; Huang, D.-Y.; Tian, Y.-B.; Zhu, Q.-H.; Zhang, Q.; Zhu, H.-H.; Xu, C. Influences of Different Source Microplastics with Different Particle Sizes and Application Rates on Soil Properties and Growth of Chinese Cabbage (*Brassica chinensis* L.). *Ecotoxicol. Environ. Saf.* **2021**, *222*, 112480. [\[CrossRef\]](#)
89. Qi, Y.; Yang, X.; Pelaez, A.M.; Huerta Lwanga, E.; Beriot, N.; Gertsen, H.; Garbeva, P.; Geissen, V. Macro- and Micro- Plastics in Soil-Plant System: Effects of Plastic Mulch Film Residues on Wheat (*Triticum aestivum*) Growth. *Sci. Total Environ.* **2018**, *645*, 1048–1056. [\[CrossRef\]](#) [\[PubMed\]](#)
90. de Souza Machado, A.A.; Lau, C.W.; Kloas, W.; Bergmann, J.; Bachelier, J.B.; Faltin, E.; Becker, R.; Görlich, A.S.; Rillig, M.C. Microplastics Can Change Soil Properties and Affect Plant Performance. *Environ. Sci. Technol.* **2019**, *53*, 6044–6052. [\[CrossRef\]](#)
91. Reay, M.K.; Greenfield, L.M.; Graf, M.; Lloyd, C.E.M.; Evershed, R.P.; Chadwick, D.R.; Jones, D.L. LDPE and Biodegradable PLA-PBAT Plastics Differentially Affect Plant-Soil Nitrogen Partitioning and Dynamics in a Hordeum Vulgare Mesocosm. *J. Hazard. Mater.* **2023**, *447*, 130825. [\[CrossRef\]](#)
92. Menicagli, V.; Balestri, E.; Fulignati, S.; Raspolli Galletti, A.M.; Lardicci, C. Plastic Litter in Coastal Sand Dunes: Degradation Behavior and Impact on Native and Non-Native Invasive Plants. *Environ. Pollut.* **2023**, *316*, 120738. [\[CrossRef\]](#)
93. Konduri, M.K.R.; Bogolu, V.R. Comparative Degradation of LDPE, HDPE and HMHDPE under Different Soil Conditions. *J. Res. Updat. Polym. Sci.* **2014**, *3*, 178–183. [\[CrossRef\]](#)
94. Wei, R.; Zimmermann, W. Microbial Enzymes for the Recycling of Recalcitrant Petroleum-Based Plastics: How Far Are We? *Microb. Biotechnol.* **2017**, *10*, 1308–1322. [\[CrossRef\]](#)
95. Ojeda, T.; Freitas, A.; Birck, K.; Dalmolin, E.; Jacques, R.; Bento, F.; Camargo, F. Degradability of Linear Polyolefins under Natural Weathering. *Polym. Degrad. Stab.* **2011**, *96*, 703–707. [\[CrossRef\]](#)
96. Pinto-Poblete, A.; Retamal-Salgado, J.; López, M.D.; Zapata, N.; Sierra-Almeida, A.; Schoebitz, M. Combined Effect of Microplastics and Cd Alters the Enzymatic Activity of Soil and the Productivity of Strawberry Plants. *Plants* **2022**, *11*, 536. [\[CrossRef\]](#) [\[PubMed\]](#)
97. Hussein, A.A.; Al-Mayaly, I.K.A.; Khudeir, S.H. Isolation, Screening and Identification of Low Density Polyethylene (LDPE) Degrading Bacteria from Contaminated Soil with Plastic Wastes. *Mesop. Environ. J.* **2015**, *1*, 4.
98. Esmaeili, A.; Pourbabaee, A.A.; Alikhani, H.A.; Shabani, F.; Esmaeili, E. Biodegradation of Low-Density Polyethylene (LDPE) by Mixed Culture of *Lysinibacillus xylanilyticus* and *Aspergillus niger* in Soil. *PLoS ONE* **2013**, *8*, e71720. [\[CrossRef\]](#) [\[PubMed\]](#)
99. Gajendiran, A.; Krishnamoorthy, S.; Abraham, J. Microbial Degradation of Low-Density Polyethylene (LDPE) by *Aspergillus clavatus* Strain JASK1 Isolated from Landfill Soil. *3 Biotech* **2016**, *6*, 52. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Bhardwaj, H.; Gupta, R.; Tiwari, A. Communities of Microbial Enzymes Associated with Biodegradation of Plastics. *J. Polym. Environ.* **2013**, *21*, 575–579. [\[CrossRef\]](#)
101. Mayer, A.M.; Staples, R.C. Laccase: New Functions for an Old Enzyme. *Phytochemistry* **2002**, *60*, 551–565. [\[CrossRef\]](#)
102. Sivan, A. New Perspectives in Plastic Biodegradation. *Curr. Opin. Biotechnol.* **2011**, *22*, 422–426. [\[CrossRef\]](#)

103. Nerín, C.; Tornés, A.R.; Domeño, C.; Cacho, J. Absorption of Pesticides on Plastic Films Used as Agricultural Soil Covers. *J. Agric. Food Chem.* **1996**, *44*, 4009–4014. [\[CrossRef\]](#)
104. Zhang, C.; Lei, Y.; Qian, J.; Qiao, Y.; Liu, J.; Li, S.; Dai, L.; Sun, K.; Guo, H.; Sui, G.; et al. Sorption of Organochlorine Pesticides on Polyethylene Microplastics in Soil Suspension. *Ecotoxicol. Environ. Saf.* **2021**, *223*, 112591. [\[CrossRef\]](#) [\[PubMed\]](#)
105. Li, M.; Wu, D.; Wu, D.; Guo, H.; Han, S. Influence of Polyethylene-Microplastic on Environmental Behaviors of Metals in Soil. *Environ. Sci. Pollut. Res.* **2021**, *28*, 28329–28336. [\[CrossRef\]](#)
106. Song, X.; Zhuang, W.; Cui, H.; Liu, M.; Gao, T.; Li, A.; Gao, Z. Interactions of Microplastics with Organic, Inorganic and Bio-Pollutants and the Ecotoxicological Effects on Terrestrial and Aquatic Organisms. *Sci. Total. Environ.* **2022**, *838*, 156068. [\[CrossRef\]](#) [\[PubMed\]](#)
107. Hüffer, T.; Metzelder, F.; Sigmund, G.; Slawek, S.; Schmidt, T.C.; Hofmann, T. Polyethylene Microplastics Influence the Transport of Organic Contaminants in Soil. *Sci. Total. Environ.* **2019**, *657*, 242–247. [\[CrossRef\]](#) [\[PubMed\]](#)
108. Huang, F.; Hu, J.; Chen, L.; Wang, Z.; Sun, S.; Zhang, W.; Jiang, H.; Luo, Y.; Wang, L.; Zeng, Y.; et al. Microplastics May Increase the Environmental Risks of Cd via Promoting Cd Uptake by Plants: A Meta-Analysis. *J. Hazard. Mater.* **2023**, *448*, 130887. [\[CrossRef\]](#) [\[PubMed\]](#)
109. Khalid, N.; Aqeel, M.; Noman, A. Microplastics Could Be a Threat to Plants in Terrestrial Systems Directly or Indirectly. *Environ. Pollut.* **2020**, *267*, 115653. [\[CrossRef\]](#)
110. Feng, X.; Wang, Q.; Sun, Y.; Zhang, S.; Wang, F. Microplastics Change Soil Properties, Heavy Metal Availability and Bacterial Community in a Pb-Zn-Contaminated Soil. *J. Hazard. Mater.* **2022**, *424*, 127364. [\[CrossRef\]](#) [\[PubMed\]](#)
111. Wen, X.; Yin, L.; Zhou, Z.; Kang, Z.; Sun, Q.; Zhang, Y.; Long, Y.; Nie, X.; Wu, Z.; Jiang, C. Microplastics Can Affect Soil Properties and Chemical Speciation of Metals in Yellow-Brown Soil. *Ecotoxicol. Environ. Saf.* **2022**, *243*, 113958. [\[CrossRef\]](#) [\[PubMed\]](#)
112. Luo, Y.; Li, L.; Feng, Y.; Li, R.; Yang, J.; Peijnenburg, W.J.G.M.; Tu, C. Quantitative Tracing of Uptake and Transport of Submicrometre Plastics in Crop Plants Using Lanthanide Chelates as a Dual-Functional Tracer. *Nat. Nanotechnol.* **2022**, *17*, 424–431. [\[CrossRef\]](#)
113. Shi, L.; Hou, Y.; Chen, Z.; Bu, Y.; Zhang, X.; Shen, Z.; Chen, Y. Impact of Polyethylene on Soil Physicochemical Properties and Characteristics of Sweet Potato Growth and Polyethylene Absorption. *Chemosphere* **2022**, *302*, 134734. [\[CrossRef\]](#) [\[PubMed\]](#)
114. Wang, F.; Wang, X.; Song, N. Polyethylene Microplastics Increase Cadmium Uptake in Lettuce (*Lactuca sativa* L.) by Altering the Soil Microenvironment. *Sci. Total. Environ.* **2021**, *784*, 147133. [\[CrossRef\]](#) [\[PubMed\]](#)
115. Zhao, M.; Li, C.; Zhang, C.; Han, B.; Wang, X.; Zhang, J.; Wang, J.; Cao, B.; Zhao, Y.; Chen, Y.; et al. Typical Microplastics in Field and Facility Agriculture Dynamically Affect Available Cadmium in Different Soil Types through Physicochemical Dynamics of Carbon, Iron and Microbes. *J. Hazard. Mater.* **2022**, *440*, 129726. [\[CrossRef\]](#) [\[PubMed\]](#)
116. Liu, Y.; Xiao, M.; Shahbaz, M.; Hu, Z.; Zhu, Z.; Lu, S.; Yu, Y.; Yao, H.; Chen, J.; Ge, T. Microplastics in Soil Can Increase Nutrient Uptake by Wheat. *J. Hazard. Mater.* **2022**, *438*, 129547. [\[CrossRef\]](#) [\[PubMed\]](#)
117. Tang, M.; Huang, Y.; Zhang, W.; Fu, T.; Zeng, T.; Huang, Y.; Yang, X. Effects of Microplastics on the Mineral Elements Absorption and Accumulation in Hydroponic Rice Seedlings (*Oryza sativa* L.). *Bull. Environ. Contam. Toxicol.* **2022**, *108*, 949–955. [\[CrossRef\]](#)
118. Gao, M.; Liu, Y.; Dong, Y.; Song, Z. Effect of Polyethylene Particles on Dibutyl Phthalate Toxicity in Lettuce (*Lactuca sativa* L.). *J. Hazard. Mater.* **2021**, *401*, 123422. [\[CrossRef\]](#)
119. Liu, S.; Wang, J.; Zhu, J.; Wang, J.; Wang, H.; Zhan, X. The Joint Toxicity of Polyethylene Microplastic and Phenanthrene to Wheat Seedlings. *Chemosphere* **2021**, *282*, 130967. [\[CrossRef\]](#)
120. Golia, E.E.; Bethanis, J.; Ntinopoulos, N.; Kaffe, G.-G.; Komnou, A.A.; Vasilou, C. Investigating the Potential of Heavy Metal Accumulation from Hemp. The Use of Industrial Hemp (*Cannabis sativa* L.) for Phytoremediation of Heavily and Moderated Polluted Soils. *Sustain. Chem. Pharm.* **2023**, *31*, 100961. [\[CrossRef\]](#)
121. Zettler, E.R.; Mincer, T.J.; Amaral-Zettler, L.A. Life in the “Plastisphere”: Microbial Communities on Plastic Marine Debris. *Environ. Sci. Technol.* **2013**, *47*, 7137–7146. [\[CrossRef\]](#) [\[PubMed\]](#)

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