

Review

Soil Microplastic Pollution Across Terrestrial Ecosystems: A Review of Sources, Distribution Patterns, Polymer Types and Environmental Implications

Eirini Tzitzira, Traianos Minos and Evangelia E. Golia *

Soil Science Laboratory, School of Agriculture, Faculty of Agriculture, Forestry and Natural Environment, Aristotle University of Thessaloniki, University Campus, 541 24 Thessaloniki, Greece; eitzitzira@uth.gr (E.T.)

* Correspondence: egolia@auth.gr; Tel.: +30-2310998809

Abstract

The present study investigates the presence, sources, and impacts of microplastics (MPs) in different soil types, including agricultural, urban, and forest areas, through a synthesis of results of published scientific papers. MPs originate from a variety of human activities, such as the widespread use of plastic mulch in agriculture and the application of organic fertilizers and treated sewage sludge, as well as from vehicle tire wear, industrial processes, and the gradual degradation of plastic products in the environment. In urban soils, the main sources of MPs are related to road traffic, industrial activity, and landfills, while in forest soils, concentrations are generally lower. However, MPs in forest areas are thought to be carried there by the air, by runoff, or from nearby areas with human activity. Available data show that larger MP particles tend to remain in the surface layers of the soil, while smaller particles can penetrate deeper soil layers, increasing their bioavailability and the likelihood of interaction with microorganisms and plant root systems. In terms of their chemical composition, polyethylene (PE) and polypropylene (PP) polymers dominate in agricultural soils, which is directly linked to agricultural practices, while polystyrene (PS) and polyvinyl chloride (PVC) are more frequently detected in urban soils. The morphological types of MPs include fragments, fibers, and films, while their color characteristics provide clues to possible sources of origin, such as plastic ground covers, tire wear, and packaging materials. Overall, the study's results underscore the growing environmental significance of MP soil pollution and highlight the need for more effective management and recycling of plastic materials, as well as for further interdisciplinary research aimed at understanding the mechanisms of transport, accumulation, and long-term ecological effects of microplastics in terrestrial ecosystems.

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1. Introduction

1.1. Historical Context and Research Trends in Terrestrial Microplastic Pollution

Microplastics (MPs), commonly defined as plastic particles with a maximum dimension smaller than 5 mm [1,2], have been extensively researched in aquatic ecosystems for their impacts on both the ecosystems themselves and on the biodiversity they support. In

contrast, research on their presence and consequences in terrestrial ecosystems has developed more gradually. This is mainly due to the uneven and constantly expanding knowledge base, with efforts varying from country to country. As noted, a substantial body of literature originates from China, considerable progress is being made in Europe, and less information is available in America [3].

Although research on terrestrial MPs has increased in the last decade, most studies have focused on agricultural and urban soils, whereas forest and other natural soils remain less explored, resulting in important knowledge gaps [4–7]. Consequently, our understanding of MP distribution, characteristics and impacts across different soil types remains incomplete. The huge increase in global plastic production since the post-industrial era has led to the widespread dispersion of plastic debris, including MP particles, which have become ubiquitous in all ecosystems, even in remote and inaccessible places [8]. This increased production leads to the creation of environmental pollutants, while interest in investigating MPs and their negative effects on soils and organisms has become an increasingly topical and important issue. Concerns mainly relate to soil structure, biodiversity and ecosystem processes, particularly under different land-use conditions [9]. Thus, in recent years, the scientific community has recognized plastic pollution as one of the most significant environmental threats [10].

Historically, the first synthetic material was created in the early 20th century and was named Bakelite. Its use was not particularly widespread, except in the military, until World War II, when its production began to increase steadily [11].

A few years before the 1930s and continuing into the 1940s, commercial production began, and the production of synthetic polymers increased rapidly as their use expanded into other areas. Global plastic production already reached about 1.5 million tonnes in the 1950s [12] and subsequently rose by approximately 728%, from roughly 50 million tonnes in 1976 to about 414 million tonnes in 2023 [13]. Given the high demand for this material and the pace of production, the OECD Global Plastics Outlook projects that global plastics production and use will roughly double to triple by 2050–2060 [14], suggesting a continued increase in environmental inputs and accumulation in terrestrial ecosystems. Importantly, MPs not only degrade environmental quality but also pose significant risks to the health of living organisms, including humans, through their persistence in soils, their mobility along the trophic chain, and their capacity to act as vectors for co-contaminants [15–17].

1.2. Plastic: Material, Production and Global Dimension

Plastics have become irreplaceable materials in our lives and are widely used worldwide due to the many advantages they offer, some of which are: their low weight, strength and durability, ease of use, the variety of products that can be produced from them, their ergonomics, and, of course, their minimal economic cost [11,18]. Other notable characteristics of MPs are their resistance to degradation and their polluting effect on the environment, as they can be toxic to ecosystems and the organisms that inhabit them [19].

Plastic is a synthetic material composed of carbon and hydrogen atoms, which are found in chains—large compounds called polymers. The length of the entangled chains that are formed determines the chemical composition of plastics [20].

In a comparison of European demand for plastics, six polymer families—polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PU), polyethylene terephthalate (PET) and polystyrene (PS)—together account for about 81.2% of converter demand by polymer type [21]. It should be noted that this figure is not directly comparable with the separate estimate that about 90.4% of total plastics produced are conventional fossil-based (petrochemical) plastics (e.g., PE, PP, PVC, PET), because the two percentages

refer to different denominators—the polymer-type composition of European demand versus the fossil-based share of global production. Only 8.7% is recycled (mechanically or chemically), while only 0.7% is bio-based and 0.1% is chemically recycled [22].

With pollution from plastics and MPs increasing steadily, now posing a major environmental challenge, it requires considerable attention [23]. According to research, only 60% of the 250 million tons of plastic produced annually is collected [24].

Taking into account research estimates, global plastic production could reach 33 billion tons annually by 2050 [25]. However, only 20% of plastics can be recycled, with the remaining 80% ending up in the environment, where they are deposited and then accumulate in both terrestrial and aquatic environments [26].

1.3. Origin and Sources of Microplastics

Rillig [27] first raised the issue about a decade ago [28]. However, there is a lack of data on the terrestrial environment, such as different types of land such as urban, agricultural, and forest, as less attention has been paid to it, despite the fact that there are significant signs of pollution [19,29,30]. In addition, it has been discovered that soils are a larger reservoir of MPs than oceans because, until recently, a significant proportion ended up in landfills [31,32].

This is quite alarming, as the introduction of small plastic particles poses significant risks. Mainly, the interactions that develop disrupt the geochemical and biophysical environment of the soil, with corresponding effects on soil microorganisms and organisms [15]. The change in soil ecology also affects plant growth [16] and the microbial communities of the soil that regulate their activities [33].

Once plastics are deposited in the environment, they undergo various degradation processes, whether natural, chemical, or biological; over time, the result is that they end up as smaller particles of the same size but with different or similar shapes. Thus, the categories into which MPs should be classified are primary and secondary MPs [1,2]. To be precise, primary MPs are manufactured for specific applications and include products such as cosmetics, pharmaceutical packaging, and materials used in industrial and mechanical processes [34].

In the secondary category of MPs, their structure comes from the gradual breakdown of larger plastics into smaller particles through a variety of complex environmental processes, which include abiotic factors—wind, temperature, and ultraviolet radiation—as well as biological mechanisms such as microbially mediated degradation and physical fragmentation by soil fauna, e.g., earthworms and microarthropods [35,36]. These factors can induce chemical changes in plastics, making them more fragile and ultimately leading to their accumulation in the soil [37,38].

The sources range from increased production and use of plastic products to improper management, resulting in enormous amounts of waste. Therefore, understanding the sources and characteristics of MP pollution is crucial for implementing effective environmental protection measures and reducing MP pollution [19].

Soil degradation caused by plastics occurs through the dispersion of plasticizer molecules on the surface of objects, with their subsequent direct runoff from the soil or breakdown by soil elements on the surface of the plastic object [39]. In general, the areas most affected by human activities are urban and rural areas, where pollution levels are high [40]. Below, we will examine in detail the sources in each soil category.

1.3.1. Urban Areas

In urban and transit areas, as well as in locations near busy roads, we encounter MPs, which originate mainly from transportation in general. Roads are probably the main source of plastic pollution due to tire wear, as rubber is usually a synthetic polymer; other sources include vehicles and boat parts [41,42]. A recent report by Chen et al. [41] presents that vehicle traffic and the extensive area covered by urban and transitional soils due to high mobility on roads cause high concentrations of MPs.

Relevant research in the Netherlands reports that aircraft tire wear accounts for 2% of total MP emissions [42]. Some reports of annual particle emissions from tires that we can cite specifically range from approximately 10,000 tons in Sweden to 110,000 tons in Germany [31].

On the other hand, industries and landfills are equally important sources of MPs [43,44]. However, the latter two contribute to a greater extent. Possible sources include the production of plastic products and by-products, packaging materials, and any other product in the industrial area. This is due to the rapid production and subsequent loss of plastic particles through illegal dumping or improper management and possible exploitation of the huge volume of waste [45]. Consequently, the total amount of waste allows MPs and nanoplastics to enter the natural environment [46].

Other factors that contribute to the accumulation of MPs in soils include natural flooding, runoff from roads, and urban centers. Drainage from roads and urban areas, when there is no retention by sewage networks (from urban or industrial wastewater), is likely to pollute the surrounding soil [44].

1.3.2. Agricultural Land

Agricultural practices and applications in recent years have been extensively researched in terms of direct and indirect pollution emissions, including plastic pollution from the introduction of plastics through organic waste such as compost. Organic fertilizers are quite likely to contain contaminated microparticles, and soil cover is also considered a major source of input. This is followed by sludge, compost, and even applications of other materials, including naturally varied agricultural products such as ropes, containers, and other tools [7,47,48].

Specifically, plastic covers, known as mulch (4–8 µm thick), are widely used to improve plant growth and can contribute positively to increasing soil temperature and water use efficiency, i.e., irrigation [48–50]. At the same time, they help reduce various types of pests that can damage plants and prevent diseases [48,51]. All of these methods of improving agriculture are among the most common ways in which MPs enter the soil [51–54].

Thus, the plastic particles that enter agricultural soils are mainly added from the plastic coating that is applied due to these positive factors. This common practice, combined with low recycling and harvesting rates, results in the accumulation of fairly large amounts of MPs in agricultural soils [33,55]. They may also enter the soil through treated wastewater for irrigation, as well as through the atmosphere, i.e., dry or wet precipitation (i.e., rain and snow) from the atmosphere.

Surface runoff and flooding act as transport pathways, frequently channeling pollutants toward road networks and residential areas and contributing to their redistribution within the environment [31,56]. Subsequently, the flow of water immediately creates pathways for MPs [45,57,58].

1.3.3. Forest Areas

Natural environments such as forests, protected areas, and refuges that are virtually unaffected by human activity have been found to contain concentrations of MPs of up to 0.002% [59]. Of course, the rich vegetation found in the natural environment can be considered a natural filter, but it is not limited to that, as it can also act as an anti-pollution mechanism in urban environments [60]. Tree combs, shoots, and roots can retain some of the MPs and help reduce their transport through water runoff or erosion by wind or other abiotic factors in the area [61].

However, containing and transporting MPs in the environment is not a way to reduce them, as their basic property, as mentioned above, is their exceptional durability. This is why plastic is such a popular material: even during the degradation process that takes place in the environment, it remains stable and does not biodegrade easily [35]. It thus remains in the natural environment for several years, with minimal changes, causing multi-level impacts [62–64].

1.3.4. Other Sources of Microplastics in Soil

The tourism sector also contributes significantly to waste pollution, as areas with intense tourism tend to have increased concentrations in the soil. Another source is the deposition of plastic or synthetic materials after they have decomposed. Synthetic fibers from clothing and household items that are discarded are also a source of MPs, as when they wear out, MPs escape through the atmospheric transport of particles or simply accumulate in waste collection areas [36].

Then, atmospheric deposition through rain, snow, or air currents can disperse fibers or MP fragments into the terrestrial ecosystem. Illegal dumping and littering near roads also contribute to environmental pollution. With the negative consequences they have on the Earth and beyond, the huge amounts of accumulation are not the only problem, as they not only enter the soil but also contribute to the increase in greenhouse gas emissions [65,66]. Consequently, soils do not merely act as a passive repository of MPs; they also constitute a medium in which MPs exert a range of negative effects, including disturbance of soil structure, alteration of microbial activity and entry into the food chain [17].

However, it is noteworthy that soil pollution has become a serious and widespread problem, mainly due to the increased production and use of plastics, as well as inadequate waste management [32].

Beyond their occurrence in soils, MPs have also been documented in a wide range of food items and in bottled drinking water, raising concerns about chronic dietary exposure of consumers [46]. Particles transferred from soil to crops, livestock products and groundwater create a continuum between soil pollution and human exposure, with reported effects ranging from local inflammatory responses to potential systemic impacts through the carriage of additives and adsorbed contaminants [17]. The recognition of this soil–food–human pathway underlines the public-health relevance of soil MP studies such as the present review.

In light of the above, the aim of the present review is to synthesize and compare the published evidence on the occurrence, characteristics and sources of MPs in agricultural, urban and forest soils. Specifically, the review (i) compiles quantitative data on polymer type, particle size, shape and color across the three land-use categories; (ii) identifies the dominant input pathways under each category and contrasts direct-input systems (agricultural and urban soils) with indirect-accumulation systems (forest soils); and (iii) highlights the main knowledge gaps and methodological limitations that should guide future research. The principal limitation of the synthesis lies in the methodological heterogeneity of the underlying studies, which is explicitly addressed in Section 2.

2. Materials and Methods

The purpose of the review is to synthesize the numerous sources and publications that aimed to investigate terrestrial ecosystems under the influence of plastic pollution. The scarcity of publications on the subject has further increased scientific interest in the issue. In this paper, we focus on the presence of MPs, on data collections that will help us better understand the extent and consequences of the pollution they cause, and on the variations observed in soils, mainly in agricultural, urban, and forest soils. Although the number of publications on terrestrial MPs has expanded rapidly in recent years, comparative syntheses across multiple land-use categories remain limited, which motivated the present work.

For this reason, and due to the complex nature of investigating such a topic, there are several perspectives.

The high occurrence of small-sized particles (<250 µm), particularly in forest and urban soils, suggests increased bioavailability and potential interaction with soil microorganisms. Experimental evidence reported in the literature indicates that certain polymers may affect bacterial diversity, while high concentrations can alter microbial community composition. These alterations may influence nutrient cycling and overall soil ecosystem stability. In this review, the overall consequences observed will be presented. This will be followed by proposals, and potential solutions aimed at reducing plastic pollution will be analyzed.

The first steps of the review aimed to find a large number of publications, and the numerous studies and papers were classified by category: soils and MPs, urban soils and MPs, agricultural soils and MPs, forest soils and MPs. This dataset included conceptual information, experimental approaches, and findings from the respective studies.

The time frame of the data (2016–2025) was selected to capture the rapid expansion of research on terrestrial MPs at the global scale, as research on MPs in soils is a relatively young field that has expanded substantially in recent years, with most of the available evidence published within the last decade [67]. Specifically, the synthesis used as a methodology was found to be advantageous in terms of reliable estimation of results due to its increased statistical power compared to individual studies [68]. It is thus a statistical tool that quantitatively describes the results of variables and therefore outcomes, drawing data from multiple studies, papers, databases, and other sources [69].

Our sources were gathered from journal databases and platforms such as ScienceDirect, Google Scholar, SpringerLink, Nature (<https://www.nature.com>), Science (<https://www.science.org>), and Environmental Research (Elsevier). The literature search was conducted using combinations of keywords including: (“microplastics” AND “soil”) OR (“microplastics” AND “agricultural soil”) OR (“microplastics” AND “urban soil”) OR (“microplastics” AND “forest soil”), combined with terms such as “distribution”, “sources”, “abundance”, “polymer type”, and “particle size”.

In the process of collecting data for the purpose of transferring the results of the synthesis into diagrams, sources with specific types of MP data were taken into account, covering data from 2016 to 2025. The complete list of publications and papers from which the study data was drawn is shown below (Figure 1) and include Sciencedirect, Nature, Springer, MDPI, Aalborg University’s Research Portal, International Journal of Agricultural and Biological Engineering, Researchgate, AKJournals, PubMed, Wageningen University & Research eDepot, ASCPublications, Proquest, and Miljodirektoratet. The total number of studies used for the diagrams is 69, which includes 80 cases for the 3 soil types (agricultural, urban and forest). In Figure 2 the Quantitative data from sources obtained for publication is being presented.

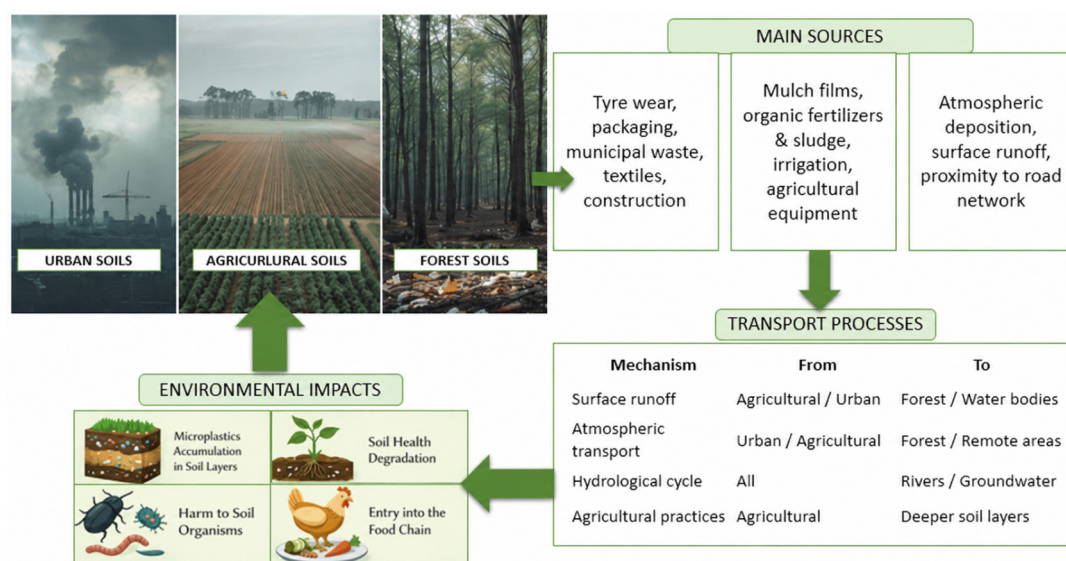


Figure 1. Sources and fate of microplastics in soil in terrestrial environments.

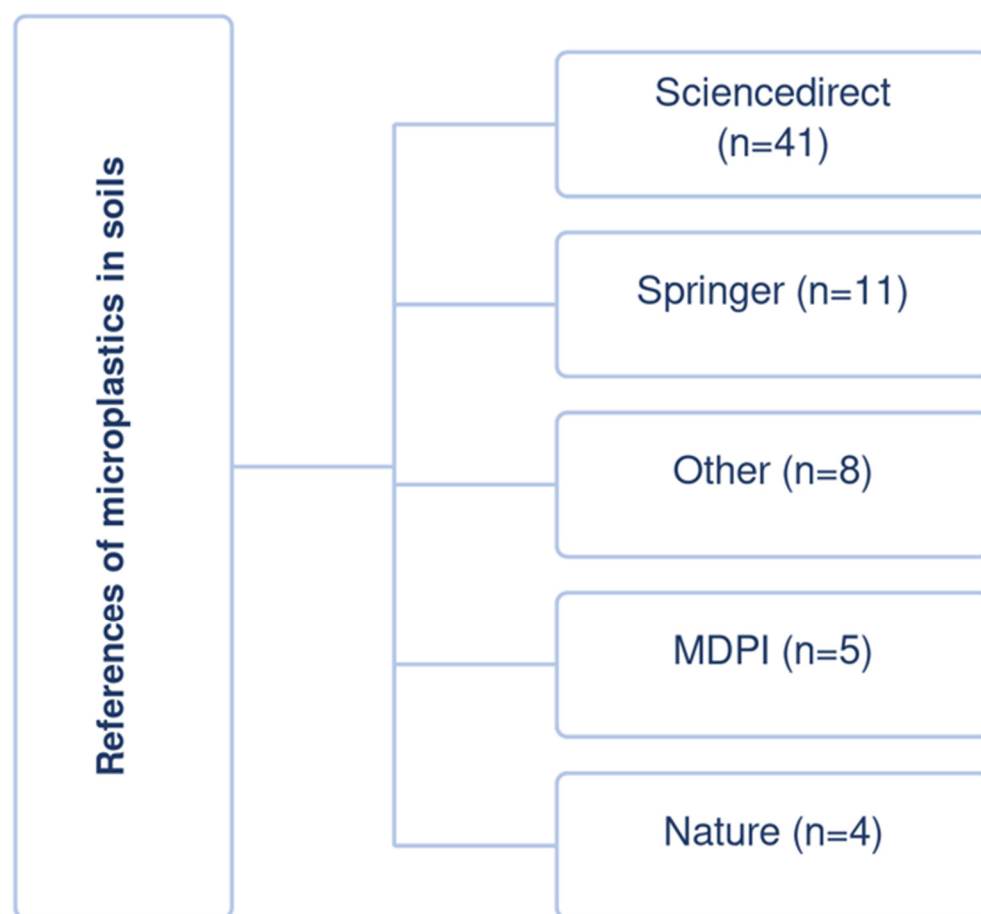


Figure 2. Quantitative data from sources obtained for publication.

This was followed by categorization of the data found in Microsoft Office Excel, with fields relating to the quantities of plastic particles, their sizes and shapes, types of polymers, soil types, and the effects and impacts caused by MP particles. The corresponding diagrams were then created using statistical analysis and are presented below with the corresponding soil categories and characteristics. Questions such as which soils have the highest concentrations, what types of plastics are found and in which categories, and what

this may indicate are answered, and further conclusions from the analysis are presented below.

Studies were included if they (i) reported primary, quantitative data on MP characteristics in real soil samples (MP abundance and/or at least one of the following attributes: polymer type, particle size, shape or color); (ii) clearly identified the land-use type of the sampled soil (agricultural, urban or forest); and (iii) specified the analytical method used for MP identification. Studies were excluded if they lacked primary quantitative data (e.g., review articles, conference papers, opinion or purely modeling studies), did not report polymer or particle information, or used an ambiguous or mixed soil classification that could not be unambiguously assigned to a single land-use category. For the purpose of this synthesis, a “case” was defined as a unique combination of a study with a single land-use category and sampling context; a publication reporting data for more than one land-use type (e.g., both agricultural and forest soils) or for clearly separated sites or regions therefore contributed more than one case, which is why the 69 included publications yielded 80 individual cases. Microplastics were defined as plastic particles with a maximum dimension below 5 mm; because the primary studies applied different lower size limits, no single lower threshold was imposed, and particles below 1 μm (nanoplastics) were noted separately where reported. Each case was assigned to the agricultural, urban or forest class on the basis of the dominant land use of the sampling site, as stated by the original authors. Owing to this variability in sampling and analytical techniques, direct quantitative comparisons should be interpreted with caution.

Through this systematic identification, selection, classification and quantitative synthesis of the available evidence according to the predefined criteria above, aggregate patterns were derived that are not visible in any individual study. The specific novelty and contributions of this unified comparative framework—which, unlike previous reviews focused on single land-use categories or global narrative overviews [3,9,30], directly contrasts agricultural, urban and forest soils—are stated in the Introduction (Section 1).

3. Results and Discussion

3.1. Geographical and Land-Use Distribution of MP Studies

The analysis of data from 69 separate publications (80 cases) provided an overview of the presence, characteristics, and potential sources of MPs in agricultural, urban, and forest soils. The evaluation of the results confirms that human activity and land use are the main factors contributing to MP input, with the highest concentrations found in agricultural soils [31,33]. Urban soils show a greater variety of colors and types of polymers, indicating multifactorial anthropogenic sources of pollution [36,44]. In contrast, forest soils show lower levels of pollution, acting mainly as recipients of pollutants transported through the atmosphere or the hydrological cycle, even in protected areas [35,70]. Analysis of particle sizes and shapes highlights that smaller particles ($<250\ \mu\text{m}$) have increased mobility and potential bioavailability, while larger units remain on the surface and are affected by agricultural practices such as plowing [71–73]. Overall, the findings highlight significant knowledge gaps, particularly in terms of experimental studies and analytical methodologies, which need to be addressed in future research to better understand the distribution and impacts of MPs in terrestrial ecosystems.

The first chart shows the number of studies conducted per country. China is the leading country in scientific publications on the subject, with a significant difference in interest in soil MPs in the three soil categories, representing 40.67% in agricultural soils, 17.24% in urban soils, and 26.66% in forest soils. Germany follows in terms of publication rates with 10.16%, 10.34%, and 20% in the respective soil categories. Looking at the chart, several European countries such as Spain, Denmark, Austria, Switzerland, Poland, and Greece

have conducted numerous studies. A limited number of studies were conducted in countries such as Mexico, Turkey, Brazil, Australia, and many others. In this diagram, they were included as a whole under the name “other,” as there were a number of individual cases. In Figure 3 the Distribution of MPs studies by country and soil group is being presented.

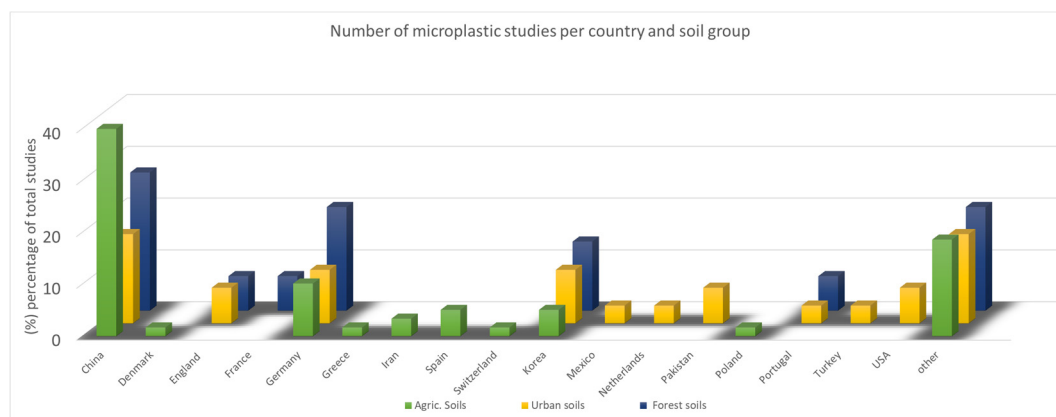


Figure 3. Distribution of MPs studies by country and soil group.

At this point, we can focus more on the possible sources observed in the studies reviewed. Quantitatively, agricultural soils accounted for the largest share of the compiled dataset (44 of the 80 cases, 55%), compared with urban (24 cases, 30%) and forest soils (12 cases, 15%), confirming that agricultural systems have been investigated far more intensively than the other two land-use types. MP concentrations vary significantly depending on the country, region, land use, and existence or practice of fertilization or the application of other soil improvers.

A noteworthy conclusion that emerged from the review is that the application of organic fertilizers does not necessarily result in low levels of pollution. In several cases, such as in Austria and Germany, compost or other types of organic fertilizers led to significant concentrations of MPs. Soil texture and type are also factors that have a significant impact. Higher quantities were observed in sandy soils than in clayey or silty soils due to their reduced capacity to retain water and nutrients.

Beyond particle and polymer characteristics, the physicochemical properties of soils themselves (such as texture, organic matter content, bulk density, pH and moisture regime) exert a strong control on the distribution and fate of MPs. Coarse, sandy soils tend to favor the vertical movement of small MPs through preferential flow pathways, whereas clay-rich or organic-matter-rich soils tend to immobilize MPs in the surface horizons and to modulate their interaction with co-contaminants [33,45]. These intrinsic soil properties should therefore be considered alongside MP characteristics when interpreting differences in concentration and morphology among land-use categories.

The dominant factor in MP inflow is human activity, with the use of plastic mulch being the most popular source of pollution, followed by fertilizers and then intensive agricultural practices. Bläsing and Amelung [31] also confirm that the main source comes from agricultural activities, including the use of sludge from wastewater treatment plants, road runoff, and compost. In the case of wastewater treatment systems, despite MP removal processes, it has been observed that MPs remain in the sludge.

Plastic pollution is intense in urban areas, including industrial and urban areas, where roads, parks, drainage wells, clothing, and laundromats are located, with huge concentrations of MPs. Pollution is estimated to be, if not definitely higher, at approximately the same levels as in agricultural areas, depending on human and industrial sources, with

comparisons varying by region and land use. For example, parks and walkways or areas with nature contained the lowest amounts.

Another factor is the location of the area in both urban and rural areas, as nearby roads or cities increase plastic pollution, as it is quite easy to transport MPs from one area to another. Relevant examples are Portugal and Chile, where the closer the concentration rates are in corresponding areas, the higher the pollution levels. It is to be expected that levels decrease the further away cities are, although some percentages in such cases may be due to flood deposits or atmospheric deposits.

Although forest soils are considered to have the lowest pollution rates, there are still concentrations that can be attributed to human activities. It is curious that MPs are found even in protected areas. Therefore, we conclude that the inputs in this case are different. An initial assessment is that they come from the water cycle, from both precipitation and groundwater, or even from nearby residential or agricultural areas. Of course, significant concentrations are found near trails.

These findings highlight a strong geographical bias in the existing literature, with a clear dominance of studies originating from China and parts of Europe. This uneven distribution limits the global representativeness of current knowledge on soil MP pollution. The dominance of agricultural studies in certain regions may also overemphasize agriculture as the primary source of MPs, potentially underestimating contributions from urban or natural systems in less studied areas. As a result, patterns observed in this study may largely reflect region-specific practices, such as intensive agriculture or waste management strategies, rather than universal trends. Consequently, caution is required when generalizing these findings to underrepresented regions.

The observed differences among soil categories can be further linked to dominant source pathways. In agricultural soils, the prevalence of studies aligns with well-documented direct inputs, such as plastic mulching, compost application, and sewage sludge, which act as primary sources of MPs. In contrast, urban soils are influenced by more diverse and diffuse sources, including tire wear, atmospheric deposition, and industrial emissions, resulting in greater variability. Forest soils, although less studied, appear to function mainly as receiving environments, where MPs are introduced indirectly through atmospheric transport, precipitation, and runoff from adjacent areas.

3.2. Showcase of the Studies Used for the Diagrams

To facilitate the comparative interpretation of the literature compiled in the present review, the data extracted from each study were synthesized into three separate tables, one for each main soil category (agricultural, urban and forest). Each row corresponds to a single study and presents, in condensed form, the characteristics of the microplastics (MPs) reported: sampling country; polymer type; particle size, shape, and color; and methodological approach. Throughout Tables 1–3, polymer abbreviations follow ISO 1043-1 [74], and color codes are abbreviated as follows: R = red, B = blue, G = green, Y = yellow, W = white, Bl = black, Tr = transparent, Br = brown, Be = beige, Gr = gray, T = translucent, and O = orange. In the “experimental setup” column, “field survey (in situ)” denotes sampling of pre-existing soils under real-world field conditions (previously labeled “natural environment”), “field study” denotes monitored field trials, and “controlled experiment” denotes laboratory, pot or mesocosm dosing studies. Cells marked “n.r.” (not reported) indicate that the corresponding attribute was not explicitly reported in the original source. Particle-size values and polymer names are presented as used in the primary studies. This format is intended both to highlight recurrent patterns across studies and to make explicit the methodological heterogeneity that characterizes soil-MP research.

Table 1. Studies on MPs in agricultural soils.

Reference	Country	Polymer Type	Particle Size	Shape	Color	Experimental Setup
[75]	Schleswig-Holstein, Northern Germany	PP, PE, Polyamide, Nylon, PMMA, PET, PVA	1–5 mm	n.r.	n.r.	Field survey (in situ)—field study
[76]	Bavaria, Germany	n.r.	1–5 mm, 5–300 mm	n.r.	n.r.	Field study
[77]	Shouguang City in Shandong Province, China	Rayon, PMMA, PES, ABS, EPC, PS, PE, PP, PU	0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm, 2.0–5.0 mm	fibers, fragments, films, foams, pellets	R, B, G, W, Bl, Gr, Tr, T, B	Field survey (in situ)—field study
[41]	Suburbs of Wuhan, China	Polyamide, PVC, PS, PE, PP, PA	0.2 mm	fibers, fragments, foams, microbeads	n.r.	Field survey (in situ)
[54]	Xinjiang Uygur Autonomous Region, China	n.r.	n.r.	n.r.	n.r.	Field survey (in situ)
[6]	Suburbs of Shanghai, China	PET, PE	0.03–16 mm	fibers, fragments, films	n.r.	Field survey (in situ)—field study
[78]	Yunnan, China	n.r.	300–5000 μm , 50–150 μm	fibers, fragments, foams, beads, sheets	n.r.	Field survey (in situ)
[78]	Chile	n.r.	300–5000 μm , 50–150 μm	fibers, fragments, foams, beads, sheets	n.r.	Field survey (in situ)
[78]	Loess Plateau of China	PE	>100 μm	fibers, fragments, foams, beads, sheets	n.r.	Field survey (in situ)
[79]	Hainan Island, China	PVC, PE, PP	200 μm , 200–500 μm , 500–1000 μm , 5000 μm	fibers, fragments, films, spheres	R, B, W, Bl	Field survey (in situ)
[80]	Suzhou Academy of Agricultural Sciences, Jiangsu, China	Polyamide, EPS, PS, PE, PP, PA	0.021–4.996 mm	fibers, fragments, films, pellets, spheres, granules	n.r.	Field study
[81]	Yeoju City Yeoju, South Korea	PET, EPS, SIS, SBR, PS, PE, PP	<1 mm, 1–5 mm	fibers, fragments, films, spheres	R, B, G, Y, W, Bl, Tr	Field survey (in situ)
[82]	Wrocław, Poland	n.r.	n.r.	fibers, fragments, films, pellets, microbeads	n.r.	Field survey (in situ)
[83]	Almería region of Spain	n.r.	n.r.	n.r.	n.r.	Field survey (in situ)
[84]	Coimbra, Portugal	PP, PE, Polyester, Rubber	116 μm , 9 μm , 2949 μm , 50–250 μm	n.r.	n.r.	Field survey (in situ)
[25]	Serbia	Polyurethane, PS, PET, PVC, PS, PE, PP, PU	386 μm , 4525 μm	n.r.	n.r.	Field study
[85]	Southwestern Soils, China	Rayon, PES, PE, PP	200–500 μm	fibers, fragments	n.r.	Field survey (in situ)—field study
[86]	Yunnan, China	n.r.	0.05–1 mm	fibers, fragments, films	n.r.	Field survey (in situ)

[4]	Spain	n.r.	50 µm	n.r.	n.r.	Field study
[87]	Denmark	n.r.	1–5 mm	n.r.	n.r.	Field survey (in situ)
[76]	Franconia—Germany	PS, PE, PP	1–5 mm	fibers, fragments, films	B, G, W, Tr	Field study
[75]	Schleswig—Holstein—Germany	PE, PP, PA	1–5 mm	n.r.	Bl	Field survey (in situ)
[88]	Central Germany—Germany	HDPE	0.3–4.91 mm	fragments, films, pellets	n.r.	Field survey (in situ)
[89]	Ontario—Canada	PMMA, PES, PS, PE, PP, PA, PU	<5 mm	n.r.	n.r.	Field study
[81]	Yeoju—Korea	PVC, SBR, PS, PE, PP	<5 mm	fibers, fragments, films, spheres	R, B, G, Y, W, Bl, Tr	Field survey (in situ)
[90]	Yongin suburb, Korea	PET, PS, PE, PP	n.r.	fibers, fragments, sheets	n.r.	Field survey (in situ)
[91]	Alar, China	PE	31 µm, 4.9 mm	fragments, films	n.r.	Field survey (in situ)
[92]	Hebei, Shandong, Hubei, Shaanxi, Jilin—China	Acrylic, PVC, PS, PE, PP, PA	0.02–5 mm, 5 mm, 0.02–0.2 mm, 0.5–1 mm	fibers, fragments, films, spheres	B, Y, W, Bl	Field survey (in situ)
[93]	Qinghai, China	n.r.	0.50 µm, 5 mm	fibers, fragments, films, pellets	n.r.	Field survey (in situ)
[94]	Enshi, China	n.r.	0–5 mm	fibers, fragments, films, foams, pellets	n.r.	Field survey (in situ)
[95]	Harbin, China	PE, PP	0.05–5 mm	n.r.	n.r.	Field survey (in situ)
[77]	Shouguang, China	Rayon, PMMA, PES, ABS, EPC, PS, PE, PP, PU	0.5–5 mm	fibers, fragments, films, foams, pellets	R, B, G, W, Bl, Gr, Tr, T, Be	Field survey (in situ)—field study
[96]	Jiangsu, China	PET, PE, PP	0.2–5 mm	n.r.	R, B, G, Y, W, Bl	n.r.
[97]	Yangtze Plain—China	Rayon, LDPE, PS, PE, PP, PA	0.1–5 mm	fibers, fragments, films	R, B, G, W, Bl	Field survey (in situ)
[98]	Jiangxi—China	PES, PE, PP	<5 mm	fibers, fragments, films, granules	n.r.	Field study
[99]	Taiwan—Taiwan	LDPE, PS, PE, PP	1–5 mm	fragments, films, foams, pellets, microbeads	W, Bl	Field survey (in situ)
[100]	Inner Mongolia	n.r.	0.45 µm, 5 mm	n.r.	n.r.	Field survey (in situ)
[4]	Spain—Murcia	n.r.	n.r.	n.r.	n.r.	Field survey (in situ)
[101]	Turkey—Adana/Karataş	SBR	55 µm, 5 mm	n.r.	n.r.	Field survey (in situ)
[20]	Lahore, Pakistan	n.r.	0.05–5 mm	fibers, fragments, sheets	n.r.	Field survey (in situ)
[75]	Northern Germany Farm-land Soils	PMMA, PET, PVA, PE, PP, PA	1–5 mm	fragments	R, B, G, Y, W, Bl, Br, Gr, O, Tr	Field study
[102]	Shaanxi Province, China	HDPE, PET, PVC, PS, PE, PP	0–0.49 mm	fibers, fragments	n.r.	Field survey (in situ)

[86]	Southwestern China	PET, PE	0.05–1 mm	fibers, fragments	n.r.	Field survey (in situ)
[103]	Fars Province, S-Central Iran	PET, PE	0.05–1 mm	fibers, films	n.r.	n.r.
[104]	China	PE, PP	0.1–0.5 mm	fibers, fragments, films, pellets, beads	R, B, G, W, Tr	Field survey (in situ)
[105]	Wallbach, Switzerland	PE, PP, PA	67 µm, 99 µm, 61 µm, 62 µm	n.r.	n.r.	field study
[106]	Greece	PE	1–5 mm	fragments	Bl	Field survey (in situ)
[107]	Szeged, Hungary	PVC, PE	1–5 mm	fibers, fragments, films, foams	n.r.	field study
[108]	Lima, Peru	PVC, PS, PE, PP	10–100 µm	fibers, fragments, spheres	R, B, W, Bl	Field survey (in situ)
[109]	Mauritius	EVA, PS, PE, PP, PA	4.9 mm	fibers, fragments, films, foams, flakes	R, B, W, Bl, Tr	Field survey (in situ)
[110]	Tunisia	Cellulose, Nylon, LDPE, HDPE, PET, PE, PP	1–5 mm	fibers, fragments	R, B, G, Y, W, Bl, Gr, Tr	Field survey (in situ)
[111]	Iran	PS, PE, PP	740 µm, 0.1–5 mm	fibers, fragments	n.r.	Field survey (in situ)—field study
[9]	Chile's Región Metropolitana	PES, EVA, PS, PE, PP, PA, PU	300 µm, 80 µm	fibers, fragments, films, pellets	n.r.	Field study

Notes. Polymer abbreviations: PE = polyethylene; PP = polypropylene; PS = polystyrene; PVC = polyvinyl chloride; PET = polyethylene terephthalate; PA = polyamide; PU = polyurethane; PES = polyester; PMMA = poly(methyl methacrylate); HDPE = high-density polyethylene; LDPE = low-density polyethylene; EPS = expanded polystyrene; EVA = ethylene-vinyl acetate; ABS = acrylonitrile butadiene styrene; SBR = styrene-butadiene rubber; SIS = styrene-isoprene-styrene copolymer; PVA = polyvinyl alcohol; EPC = ethylene-propylene copolymer; Nylon = polyamide; Rayon = regenerated cellulose (rayon). Color codes: R = red; B = blue; G = green; Y = yellow; W = white; Bl = black; Tr = transparent; Br = brown; Be = beige; Gr = gray; T = translucent; O = orange. n.r. = not reported. In the “experimental setup” column, “field survey (in situ)” denotes sampling of pre-existing soils under real-world field conditions, “field study” a monitored field trial, and “controlled experiment” a laboratory, pot or mesocosm dosing study.

Table 1 compiles 44 case entries on MPs in agricultural soils and represents the most data-rich of the three soil categories considered here. The polyolefins dominate the polymer profile, with polyethylene (PE) and polypropylene (PP) reported in the vast majority of studies, followed by PS, PET, PA and PVC—a distribution that is fully consistent with the use of plastic mulching films, the spreading of sewage sludge and the contribution of degraded irrigation pipes. In terms of morphology, fragments and fibers prevail, but the substantial presence of films (~23 records) clearly distinguishes agricultural from urban and forest soils and is attributable mainly to partially degraded mulching films. The color distribution is dominated by white, black, blue and red shades, which is again coherent with packaging materials, irrigation accessories and mulching films. Each color is correlated to a letter so as not to overcomplicate the table. The letter R corresponds to red, B to blue, G to green, Y to yellow, W to white, Bl to black, Tr to transparent, Br to brown, Be to beige, Gr to gray, T to translucent and O to orange. Methodologically, most studies are observational and conducted as in situ field surveys (~65%), with a significant share corresponding to field studies, whereas the geographic distribution remains strongly skewed

towards China and Europe, with only isolated contributions from South America, Africa and the Middle East.

Table 2 presents 24 cases focused on urban soils and reveals a greater diversity of sources compared with the agricultural category. PE remains the most reported polymer, but the share of PS, PVC and PET is markedly higher, an observation consistent with the larger contribution of urban waste, packaging and construction-related materials. Fibers and fragments dominate the morphological profile in nearly equal proportions, with the higher frequency of fibers reflecting the increased input from textiles and atmospheric deposition that characterizes urban environments. The color palette is noticeably more diverse than in the other categories (black, red, blue, white and green appear with comparable frequencies), pointing to the multifactorial anthropogenic sources typical of urban areas (packaging, textiles, household waste, road markings and tire-wear particles). As in the previous table, each letter is correlated to a color so as to simplify the table. The letter R corresponds to red, B to blue, G to green, Y to yellow, W to white, Bl to black, Tr to transparent, Be to beige, and Gr to gray. Almost all studies (~87%) were carried out as in situ field surveys, with virtually no experimental approaches, which underscores the existing gap in mechanistic, controlled-condition research on MPs in urban soils.

Table 2. Studies used for MPs in urban soils.

Reference	Country	Polymer Type	Particle Size	Shape	Color	Experimental Setup
[41]	Suburbs of Wuhan, China	PVC, PS, PE, PP, PA	0.2–5 mm	fibers, fragments, foams, microbeads	R, B, G, Bl, Br, Tr	Field survey (in situ)
[78]	Chile	Polyester, Acrylic, Nylon, LDPE, PVC	300–5000 µm, 50–150 µm	fibers, fragments, pellets	n.r.	Field survey (in situ)
[81]	Yeoju City, Yeoju, South Korea	PET, EPS, SIS, SBR, PS, PE, PP	1–5 mm	fibers, fragments, films, spheres	R, B, G, Y, W, Bl, Tr	Field survey (in situ)
[82]	Poland	LDPE, PET	n.r.	fibers, fragments, films, pellets	n.r.	Field survey (in situ)
[84]	Coimbra, Portugal	PVC, PE, PP	0.009–2.949 mm	n.r.	n.r.	Field survey (in situ)
[112]	Amsterdam, Netherlands	Polyamide, LDPE, PAC, PVC, PS, PP, PA, PU	0.37 mm, 0.40 mm, 0.19–0.40 mm, 0.25 mm	n.r.	n.r.	n.r.
[113]	Phoenix and surrounding areas of the Sonoran Desert	PVC, PES, PS, PE, PP, PA	5 µm, 5000 µm, 0.05–5 mm	fibers, fragments	n.r.	Field survey (in situ)
[114]	Istanbul, Turkey	PMMA, POM, PE	<1 mm	fibers, fragments, pellets	R, Y, W	Field survey (in situ)
[115]	Oxford, central and southern England (UK)	PES, PS, PE, PP, PA	0.025–0.567 mm	fragments, films, foams	n.r.	Field survey (in situ)
[20]	Lahore, Pakistan, Norway	PET, PES, PS, PE, PA	0.05–5 mm, 0.01–0.05 mm	fibers, films	n.r.	Field survey (in situ)
[116]	Norway	n.r.	n.r.	n.r.	n.r.	Field survey (in situ)
[117]	Mexico	PS, PE	0.01–0.05 mm	fibers	n.r.	Field study
[43]	Sydney, Australia	PET, PVC, PS, PE, PP	50 µm	beads	n.r.	Field study
[118]	Lanzhou City, China	PMMA, PET, PVC, PS, PE, PA	0.05–5 mm	fibers, fragments	B, Bl, Tr	Field survey (in situ)
[119]	Henstedt-Ulzburg—Hamburg, Germany	PET, PVA, EVA, PE	0.063–5 mm	fibers, fragments	n.r.	n.r.

[120]	Central London, UK	PET, PA	n.r.	fibers, fragments, spheres	n.r.	Field survey (in situ)
[121]	São Paulo Megacity, Brazil	PET, PS, PE	0.005–1.08 mm	fibers, fragments, foams, spheres	n.r.	Field survey (in situ)
[122]	Ho Chi Minh City, Vietnam	PVC, PE	0.3–5 mm	fragments, films	n.r.	Field survey (in situ)
[123]	Haizhu District, China	PS, PE	n.r.	fragments	n.r.	Field survey (in situ)
[124]	Seoul, Korea	PMMA, PET, PVC, PS, PE, PP, PA	n.r.	fibers, fragments, films, granules	W, Bl, Gr, Be	Field survey (in situ)
[81]	Yeoju—Korea	PVC, SBR, PS, PE, PP	<5 mm	fibers, fragments, films, spheres	R, B, G, Y, W, Bl, Tr	Field survey (in situ)
[125]	Green-belt soil—China	PS, PE	0.02–5.00 mm	fibers	Bl	Field survey (in situ)
[126]	Paris—France	Rayon, PET, PA, PU	200–600 µm	n.r.	n.r.	Field survey (in situ)
[20]	Lahore (roadside soil)—Pakistan	PET, PS, PE	55 µm, 5 mm	fibers, films	n.r.	Field survey (in situ)
[127]	Toruń, Poland	PVC, PE, PP, PU	0.4–3 mm	fibers, fragments, films, spheres	R, B, G, Y, W, Bl, Tr	Field study
[128]	Guangzhou's core urban districts, China	PET, PVC, PE, PP	0.07–5 mm	fibers, fragments, films, foams	R, B, G, W, Bl	Field survey (in situ)

Notes. Polymer abbreviations: PE = polyethylene; PP = polypropylene; PS = polystyrene; PVC = polyvinyl chloride; PET = polyethylene terephthalate; PA = polyamide; PU = polyurethane; PES = polyester; PMMA = poly(methyl methacrylate); LDPE = low-density polyethylene; EPS = expanded polystyrene; EVA = ethylene-vinyl acetate; SBR = styrene-butadiene rubber; SIS = styrene-isoprene-styrene copolymer; POM = polyoxymethylene; PAC = polyacrylate; PVA = polyvinyl alcohol; Nylon = polyamide; Rayon = regenerated cellulose (rayon). Color codes: R = red; B = blue; G = green; Y = yellow; W = white; Bl = black; Tr = transparent; Br = brown; Be = beige; Gr = gray. n.r. = not reported. In the “experimental setup” column, “field survey (in situ)” denotes sampling of pre-existing soils under real-world field conditions, “field study” a monitored field trial, and “controlled experiment” a laboratory, pot or mesocosm dosing study.

Table 3 includes 12 cases (the smallest dataset of the three categories), which, in itself, highlights the existing research gap concerning MPs in forest ecosystems. Even within this limited sample, however, clear patterns emerge: PE and PP remain the most frequently reported polymers, but the relative frequency of PET and polyester fibers is noticeably higher than in agricultural or urban soils, reinforcing the hypothesis that forest soils function primarily as receptors of atmospherically transported fibers. As regards morphology, fragments and fibers dominate, while the relatively important presence of films suggests inputs from adjacent agricultural activities or transport by surface runoff. As in the previous tables (Tables 1 and 2), each letter is correlated to a color so as to simplify the table. The letter R corresponds to red, B to blue, G to green, Y to yellow, W to white, Bl to black and Tr to transparent. The color distribution is dominated by blue, white, yellow and transparent particles, with a lower frequency of intensely colored fragments—a pattern likely reflecting prolonged photochemical and mechanical weathering and the consequent fading of particles. Sampling is performed almost exclusively as in situ field surveys at variable depths (from 0 to 5 cm down to 15–30 cm), while the geographical coverage remains fragmentary (Europe, East Asia, Australia, Canada), reinforcing the need for more systematic and extensive surveys in forest ecosystems.

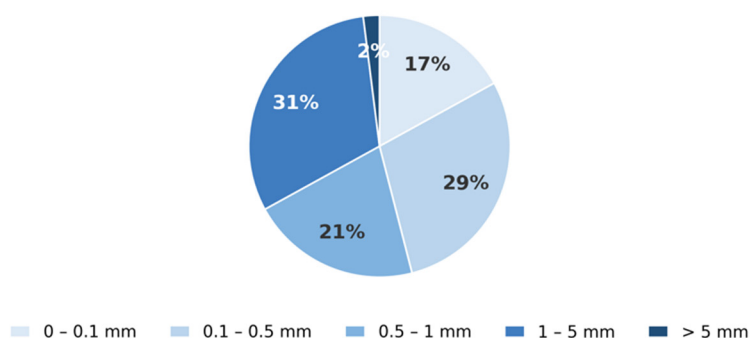
Table 3. Studies used for MPs in forest soils.

Reference	Country	Polymer Type	Particle Size	Shape	Color	Experimental Setup
[129]	Toolangi, Victoria, Australia	PE, Polyester, LDPE, PET	n.r.	fibers	n.r.	n.r.
[81]	Yeoju City, Yeoju, South Korea	PET, EPS, SIS, SBR, PS, PE, PP	<1 mm, 1–5 mm	fibers, fragments, films, spheres	R, B, G, Y, W, Bl, Tr	Topsoil (0–5 cm)
[84]	Coimbra, Portugal	PP, PE, Polyester	0.05–0.25 mm	n.r.	n.r.	0–10 cm
[81]	Yeoju—Korea	SIS, SBR	<5 mm	fibers, fragments, films	R, B, Y, W, Bl, Tr	0–5 cm
[92]	Hebei, Shandong, Hubei, Shaanxi, Jilin—China	Acrylic, PVC, PS, PE, PP, PA	0.2 mm	fibers, fragments, films, spheres	B, Y, W, Bl	n.r.
[130]	Oxford, central and southern England (UK)	Polyester, PET, PS, PE, PP	0.025–0.567 mm	fragments, films, foams	n.r.	n.r.
[85]	Southwestern Soils, China	Rayon, PES, PE, PP	200–500 µm	fibers, fragments	B, G, Y	0–20 cm
[131]	South Central Ontario, Canada	PET, PE	20–5000 µm	fibers, fragments	n.r.	n.r.
[104]	China	PE, PP	0.1–0.5 mm	fibers, fragments, films, pellets, beads	R, B, G, W, Tr	0–10 cm
[70]	Darmstadt, Germany	PMMA, PE, PP, PA	76 µm, 0.5–1 mm	n.r.	n.r.	n.r.
[132]	Germany	EPDM, PVA, PE, PA	0.3–6 mm	fragments, films	W, Tr	5 cm, 5–15 cm, 15–30 cm
[133]	Uttarakhand, India	PET, PE, PP, PA, PC	0.1–5 mm	fibers, fragments, films, foams, pellets	R, B, G, Y, W, Bl, Tr	0–20 cm

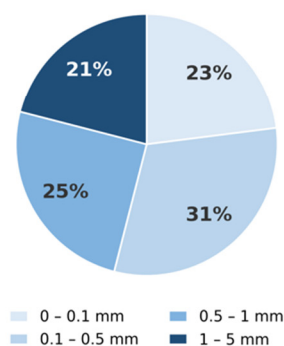
Notes. Polymer abbreviations: PE = polyethylene; PP = polypropylene; PS = polystyrene; PVC = polyvinyl chloride; PET = polyethylene terephthalate; PA = polyamide; PES = polyester; PMMA = poly(methyl methacrylate); LDPE = low-density polyethylene; EPS = expanded polystyrene; SBR = styrene-butadiene rubber; SIS = styrene-isoprene-styrene copolymer; PC = polycarbonate; EPDM = ethylene-propylene-diene monomer rubber; PVA = polyvinyl alcohol; Rayon = regenerated cellulose (rayon). Color codes: R = red; B = blue; G = green; Y = yellow; W = white; Bl = black; Tr = transparent. n.r. = not reported. In the “experimental setup” column, “field survey (in situ)” denotes sampling of pre-existing soils under real-world field conditions, “field study” a monitored field trial, and “controlled experiment” a laboratory, pot or mesocosm dosing study.

3.3. Particle Size Distribution and Bioavailability

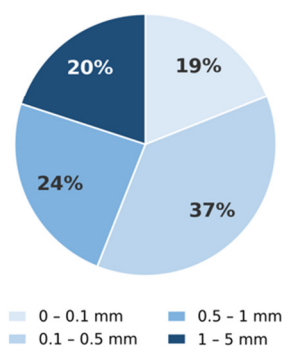
Another parameter that was studied concerns the size of MPs. Larger particles, i.e., mesoplastics (5–25 mm) and larger MPs (1–5 mm), tend to remain in the surface layers of the soil, whereas smaller MPs (typically <1 mm, and, in particular, the <250 µm fraction) and nanoplastics (<1 µm) are more readily transported to deeper soil layers. Of course, their presence in other locations and deeper in the soil is due to their transport, which may be caused by the farming practices used. Reports have noted that in plowed soils, there were high concentrations of MPs, especially on the soil surface, while at the same time, such agricultural practices are a means of spreading plastic into deeper layers. Figure 4 shows a wide range of particle sizes. One observation we can make at this point is that 2% are larger than 5 mm, while no such result was observed in urban and forest soils.

Size of the MPs found in agricultural soils

(a)

Size of the MPs found in urban soils

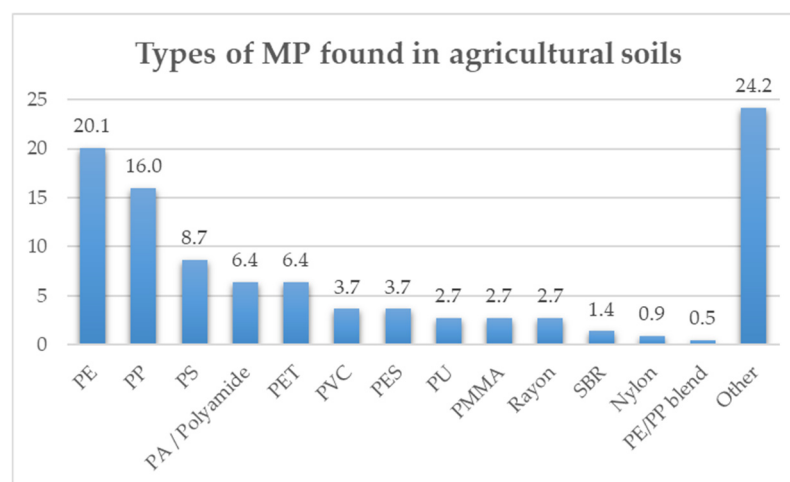
(b)

Size of the MPs found in forest soils

(c)

Figure 4. MP size distribution in: (a) agricultural soils, (b) urban soils, (c) forest soils.

In Figure 5, the sizes of MPs found in most urban soils are quite small in diameter (0.1–0.5 mm) and therefore move quite easily, are difficult to detect, and are quite likely to be bioavailable to soil microorganisms or plants. The next most common size range is medium, i.e., 0.5–1 mm, as shown in the diagram below.



(a)

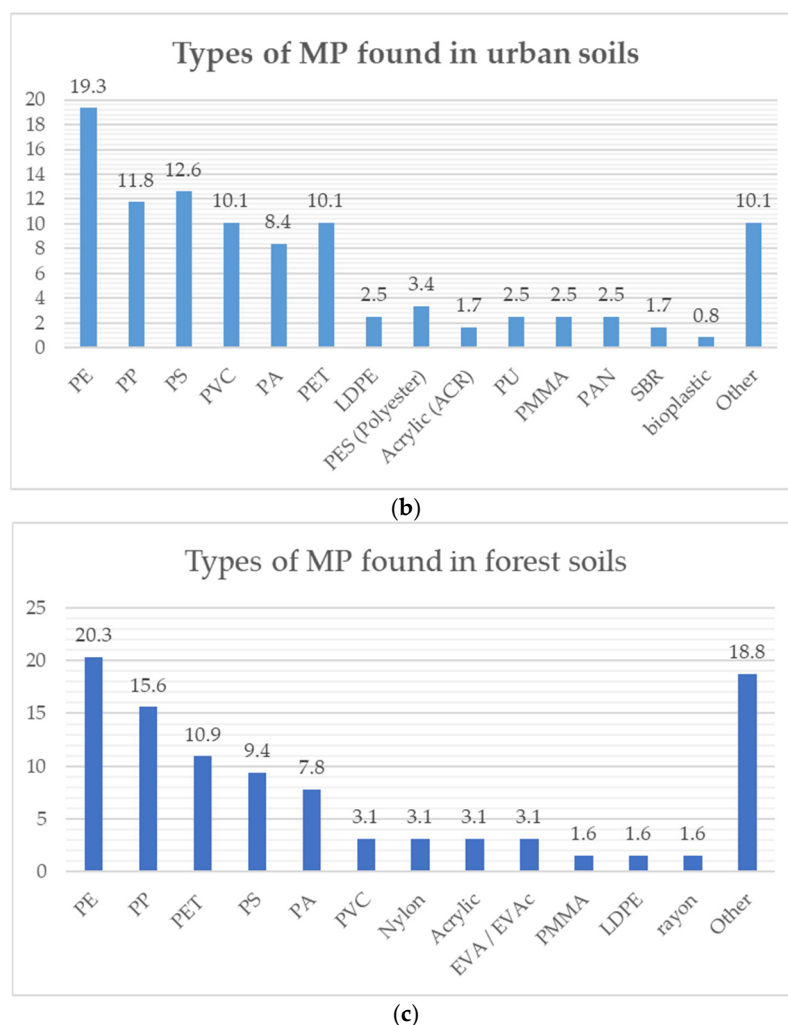


Figure 5. Percentage of publications on types of MPs in: (a) agricultural soils, (b) urban soils, (c) forest soils.

The majority of particles in forest soils, as shown in Figure 5b, were found to be small. The most common size was very small (<250 μm), facilitating transport in the soil volume and bioavailability to microorganisms or plants through their root system. Therefore, we could characterize them as potentially dangerous due to their bioavailability. However, such an environment can act defensively, utilizing rich vegetation to limit plastic pollution through various processes carried out by plant organisms.

A major parameter related to the size of MPs observed in soil categories is land-use type. Of course, other characteristics besides size include the shapes and colors of MPs. Corresponding to the type of land use being studied, it becomes easier to identify the origin of the plastic particle found, as well as the degree of accumulation and degradation.

The observed dominance of smaller MP fractions can be attributed to both fragmentation processes and transport mechanisms within the soil matrix. Mechanical breakdown (e.g., tillage in agricultural soils), combined with abiotic degradation such as UV radiation and temperature fluctuations, progressively reduces particle size. In addition, preferential flow pathways, bioturbation, and water infiltration facilitate the vertical movement of smaller particles, allowing them to penetrate deeper soil layers compared to larger fragments. The predominance of smaller MP particles is particularly important from an ecological perspective, as these fractions exhibit higher surface area-to-volume ratios, enhancing their potential to adsorb contaminants and interact with soil microorganisms and

plant roots [71–73]. This increases not only their bioavailability but also their role as vectors of pollutants within the soil system. Of course, we must be aware that the presence of plastics on the surface alone does not fully reflect soil pollution. The decomposition and incorporation of plastics into the soil is likely to be slow.

The differences observed between soil types highlight the role of land use in controlling MP size distribution. Agricultural soils exhibit a wider size range, reflecting continuous input and mechanical disturbance (e.g., plowing), which promotes both fragmentation and redistribution. In contrast, urban and forest soils are dominated by smaller particles, suggesting that MPs in these systems are primarily introduced through secondary pathways, such as atmospheric deposition and runoff, rather than direct input of larger plastic materials. These findings suggest that MP size distribution is not merely a descriptive parameter but a key factor controlling their mobility, persistence, and ecological impact within different soil environments.

3.4. Polymer Composition Across Land-Use Types

Continuing the analysis of characteristics, we see the types of MPs in Figure 5a concerning agricultural soils. The largest percentage consists of PE and PP, which are the most widespread globally due to their increased use in products such as soil covers, packaging, and irrigation materials. The distribution of polymer types can be interpreted as a fingerprint of dominant MP sources across different land-use systems. The prevalence of PE and PP in agricultural soils reflects their direct application through plastic mulching films, irrigation materials, and agricultural packaging.

There was a wide range of plastics found in urban soils, as shown in Figure 5b, with PE, PP, PS, and PVC found in the highest percentages. The sources are likely to be packaging materials or various consumer goods. In contrast, the higher occurrence of polymers such as PVC and PS in urban soil studies indicates more heterogeneous and diffuse sources, including construction materials, packaging waste, and traffic-related emissions. A clear distinction emerges between soil types, with PVC being more prevalent in urban soils, while PE dominates in agricultural systems.

In forest soils, the presence of polymers such as PET and PLA suggests inputs through atmospheric deposition, litterfall, and tourism-related activities. Unlike agricultural systems, where inputs are continuous and direct, forest environments accumulate MPs over time through indirect pathways. Microbial interactions may influence the degradation of certain polymers; however, their persistence indicates that biological processes alone are insufficient to significantly reduce MP accumulation [65].

It was also observed that some types of polymers cause a reduction in the moisture available to plants. In other cases, such as at high concentrations, they increased the abundance of specific bacterial communities. PLA was also frequently detected in forest soils, which may reflect its increasing use as a biodegradable alternative, although its persistence suggests limited degradation under natural conditions. The greatest contrast was between natural and anthropogenically influenced forests. PLA MPs, like other MPs, may be widespread due to atmospheric deposition, entrapment in the leaf litter layer, tourism and recreational activities (e.g., hiking and hunting) and their slow natural degradation, which allows them to accumulate over time.

The contrast between soil types highlights the difference between direct and indirect input systems. Agricultural soils are primarily influenced by direct and repeated inputs of specific polymers, whereas urban soils exhibit a more diverse polymer composition due to multiple diffuse sources. Forest soils, on the other hand, are dominated by polymers associated with long-range transport and secondary deposition, indicating their role as accumulation environments rather than primary sources [35].

The variability in polymer composition also has important environmental implications, as different polymers exhibit distinct physicochemical properties, influencing their degradation behavior, interaction with contaminants, and overall ecological risk within soil systems [36].

3.5. Morphological Characteristics: Fragments, Fibers and Films

In Figure 6a, fragments and fibers were found in greater quantities than other forms, followed by films. In Figure 6b, we again find that the same shapes have higher percentages compared to others, followed by spherical shapes and then the rest. However, in Figure 6c, apart from fragments, we observe that films have a high percentage of occurrence in forest soils, in contrast to urban and agricultural soils.

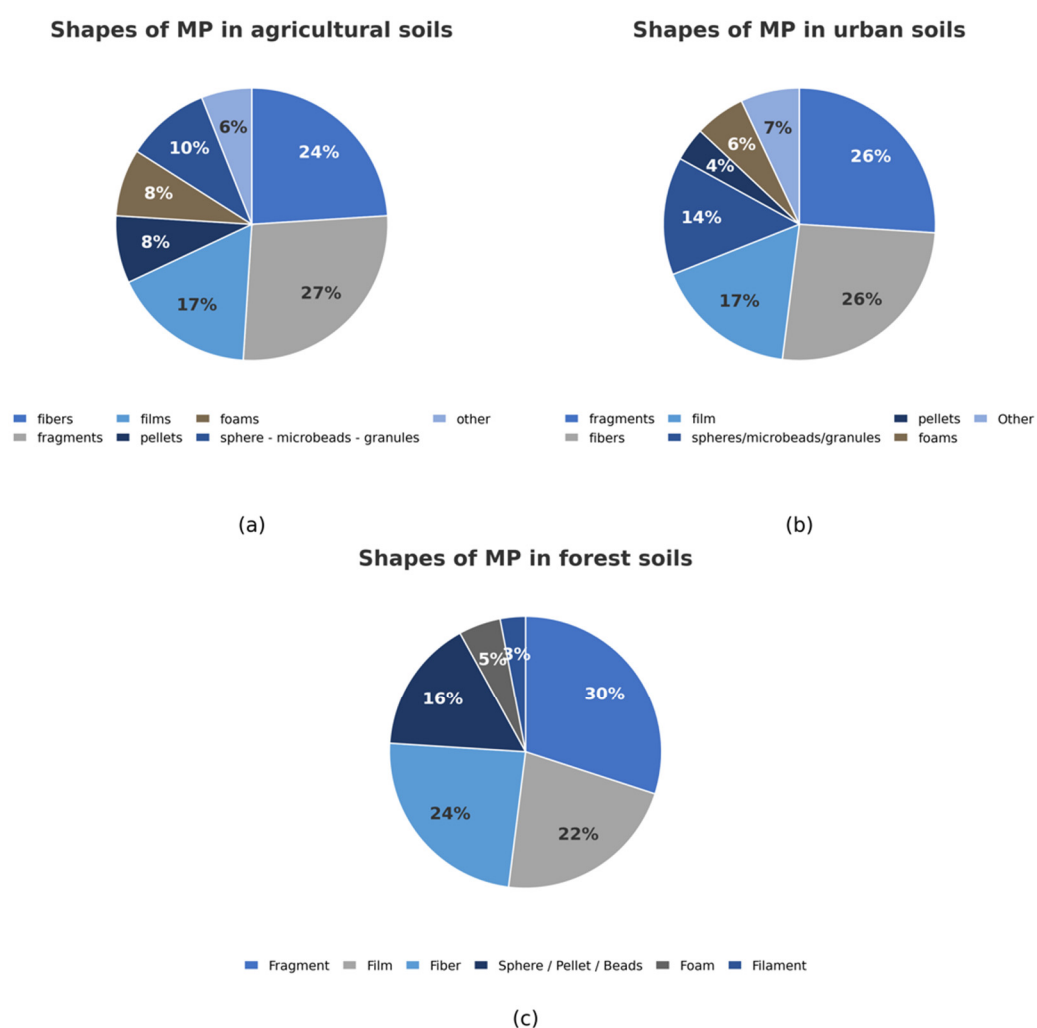


Figure 6. Percentage of publications on MP forms in: (a) agricultural soils; (b) urban soils (c) forest soils.

The dominance of fragments and fibers across all soil types suggests that secondary MPs, derived from the breakdown of larger plastic materials, represent the primary form present in soils. Fibers are commonly associated with textile sources and atmospheric deposition, whereas fragments are indicative of physical degradation of larger plastic items. The increased presence of films in agricultural soils can be directly linked to plastic mulching practices.

3.6. Color Characteristics and Weathering

The colors of the particles found are likely to be indicative of the type of product or source they come from, for example, soil cover, car tires, or some type of packaging. At this point, it is best to refer to each soil category separately, as there are several differences between them in terms of both their sources, i.e., their possible origin, and the condition of the MPs. The results are presented in Figure 7.

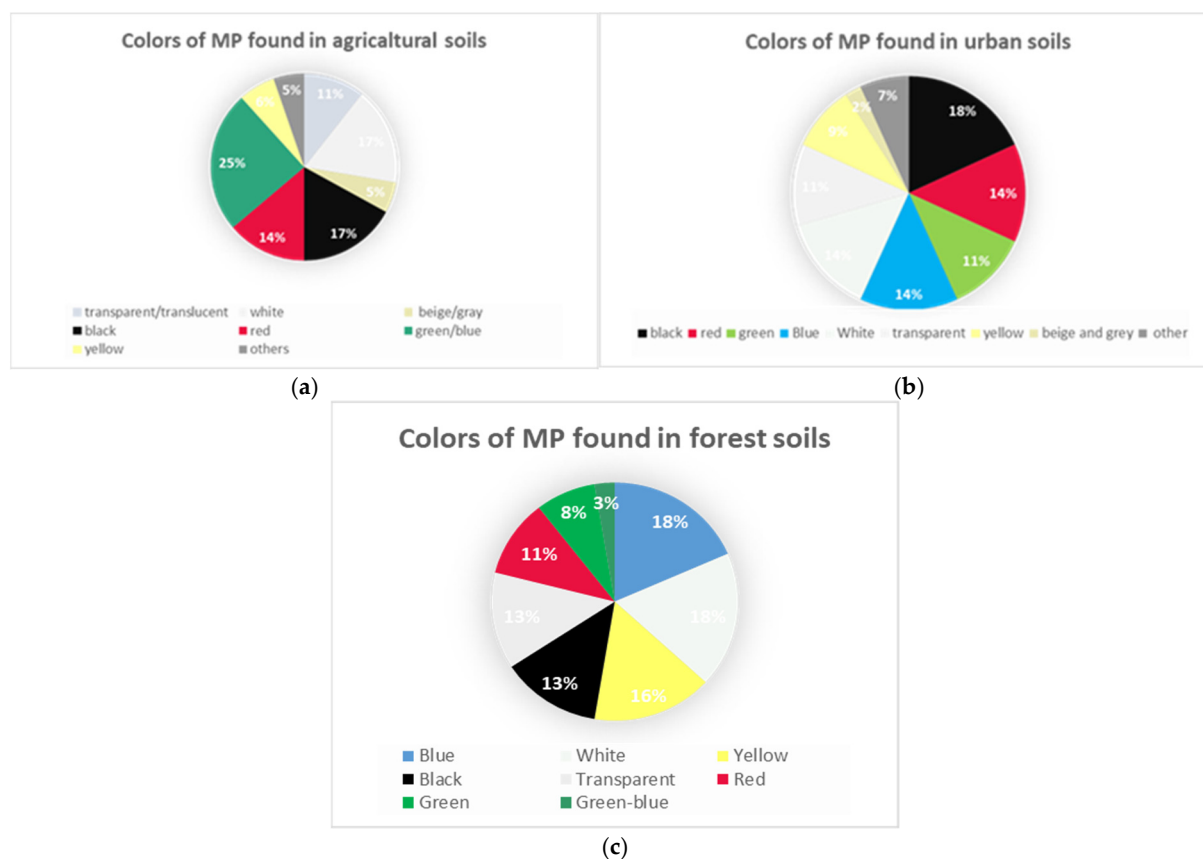


Figure 7. Percentage of publications on the colors of MPs in: (a) agricultural soils; (b) urban soils (c) forest soils.

With regard to agricultural land, there was a strong presence of green–blue (24.47%), black (17.02%), and white (17.02%) colors, which, apart from mulch, may be from irrigation pipes or other agricultural tools or materials. In general, there was not much diversity in color. In urban areas, the highest percentages of colors were found to be black (18.18%), red, white, and blue (13.64%). Given the urban landscape and the colors we encountered, most of the plastic types recovered were related to packaging, waste disposal, textiles, and construction work, suggesting that the main sources of MPs are multiple anthropogenic sources (packaging, textiles, urban waste). In general, there was greater color variety compared to the other two categories we investigated. In Figure 8 the Percentage of publications on the colors of MPs in agricultural, urban and forest soils is being presented.

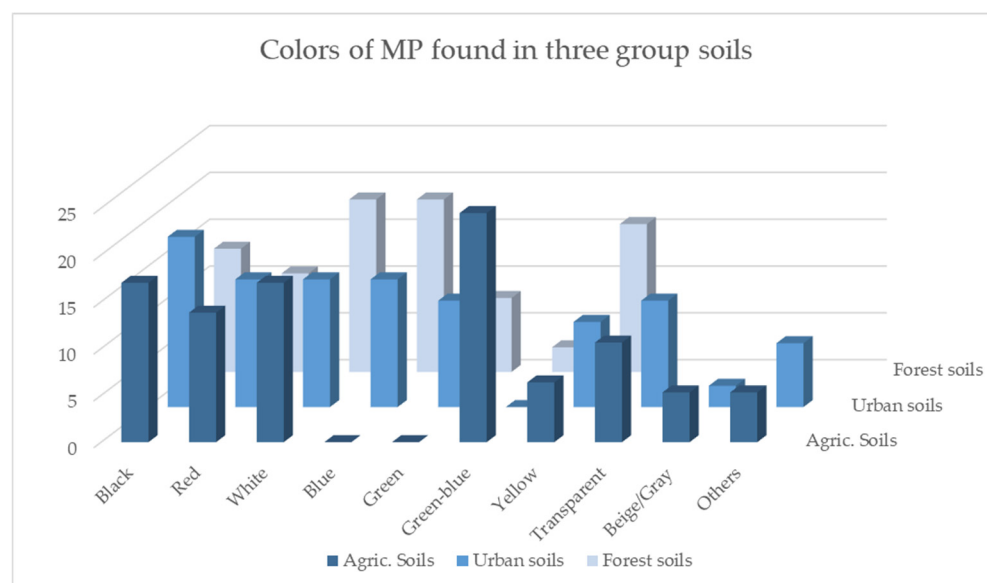


Figure 8. Percentage of publications on the colors of MPs in agricultural, urban and forest soils.

In the last group of forest soils, there was less color variety, with black and red appearing at lower rates than in agricultural and urban soils. Here, white (18.42%), blue (18.42%), and yellow (15.79%) dominated. A large percentage of light-colored MPs were found, which may indicate long-term exposure and, consequently, natural wear and tear. We believe that there were fewer direct sources and that many concentrations may have been due to transport by air or water. In conclusion, we could say that forest soils function more as receivers compared to agricultural and urban soils, which are at greater risk of exposure to pollution.

Color distribution may also reflect the degree of environmental exposure and aging of MPs. Lighter or faded colors are often associated with prolonged weathering and degradation processes, whereas more vivid colors may indicate more recent inputs. This further supports the distinction between direct-input systems (agricultural and urban soils) and indirect accumulation systems (forest soils) [134].

3.7. Methodological Approaches and Overall Synthesis

The analysis of methodological approaches shows that studies in natural environments predominate in all three soil categories, with higher percentages in urban (87.5%) and forest soils (80.0%) and slightly lower ones in agricultural soils (65.0%). Field studies are more common in agricultural soils (26.7%) than in urban (12.5%) and forest (13.3%) soils. Experimental or combined approaches remain limited, occurring only in agricultural (8.3%) and forest (6.7%) areas, while they are completely absent from urban areas, indicating a significant research gap in the investigation of controlled mechanisms.

The synthesis that followed the collection of publications gave us a rather interesting picture of the existence, characteristics studied, and sources of MPs investigated in agricultural, urban, and forest areas. The direct correlation, as mentioned in other reports, is that human activity and land use have the greatest impact on these soils, exacerbating their pollution.

In fact, the most studied soil category is clearly agricultural soil, from which we have a more complete picture of the existence of MPs and their characteristics. Of course, with regard to this observation, we could say that there seems to be concern about the impact of MPs on agricultural production and soil fertility [69]. The sources of MPs are specific activities and products such as mulching, organic fertilizers, and sludge, although the variety of colors was wide. A wide variety of colors and several types of polymers were also

observed in urban soils, indicating the multifactorial anthropogenic activities carried out in such soils. Our literature also mentioned that surface runoff and atmospheric transport play a major role here.

Overall, we can point out that despite the large number of publications, the application of experimental methods remains limited, although this situation is gradually improving. Furthermore, the lack of specific analytical procedures that yield more effective results makes comparisons between different studies difficult. Another fundamental problem that needs to be addressed is the uneven distribution of publications. As mentioned earlier, China and Central Europe have a large number of publications, while other countries are gradually catching up. This can lead to significant differences in MP analysis methods, thus affecting research conclusions.

In conclusion, the synthesis presented here points to three specific directions for further work. First, comparative field studies that combine standardized sampling and analytical protocols across agricultural, urban and forest soils are required in order to disentangle real differences in MP loads from methodological artifacts. Second, controlled experimental investigations are needed to characterize the ecotoxicological response of soil microbiota and plants to the dominant polymers identified in this review (PE, PP, PS, PVC). Third, long-term monitoring programs are necessary to track the fate of MPs along the soil profile and toward groundwater, especially in areas adjacent to urban and agricultural centers. Together, such efforts would support the design of evidence-based land management practices and prevention-oriented policies aimed at reducing the input and persistence of MPs in terrestrial ecosystems.

While the present synthesis focuses on the comparative characterization of MPs across land-use types, we acknowledge that several frontier directions in soil MP research deserve dedicated attention. These include: (i) the migration and transformation of MPs along the soil profile and toward groundwater, controlled by abiotic factors and by the soil biophysical environment [15,45]; (ii) aging and fragmentation processes that progressively generate secondary nanoplastics with distinct mobility and reactivity [35,55]; (iii) rhizosphere interactions, including effects of MPs on root architecture, plant growth and crop performance [16,33]; (iv) shifts in soil microbial community composition and metabolic activity in the presence of MPs, with cascading effects on nutrient cycling [15,33]; and (v) the role of MPs as carriers of co-contaminants such as heavy metals and organic pollutants, which markedly increases their ecological risk [19,36,45]. The polymer, size, shape and color fingerprints reported here provide a comparative baseline against which such mechanistic and ecotoxicological investigations can be framed in the future.

It should be emphasized that the studies compiled in this review differ considerably in sampling depth, extraction protocols, identification techniques and lower particle-size thresholds. This methodological heterogeneity is itself one of the key findings of the synthesis, as it constrains direct quantitative comparison and currently precludes the application of formal meta-analytical weighting. The percentages reported here should therefore be read as descriptive comparative fingerprints, not as effect-size estimates, and the standardization of analytical workflows must be regarded as a priority before robust mechanistic conclusions can be drawn at the global scale.

4. Conclusions

This review compiled 80 cases from 69 studies and showed that agricultural soils dominate both the available evidence (55% of all cases) and the reported MP loads; that polyethylene (PE) and polypropylene (PP) are the most frequent polymers across all land uses, while polystyrene (PS) and polyvinyl chloride (PVC) are enriched in urban soils and polyethylene terephthalate (PET) and polyester fibers in forest soils; and that fragments

and fibers are the dominant particle morphologies. The present synthesis offers three specific contributions beyond previously available descriptive reviews of soil MPs. First, by jointly analyzing multiple studies spanning agricultural, urban and forest soils within a single comparative framework, it establishes a baseline of polymer fingerprints, particle sizes, shape distributions and color characteristics that can be used as a reference for future investigations. Second, it identifies forest soils as accumulation environments dominated by indirect input pathways (atmospheric deposition, surface runoff and entrapment in the leaf-litter layer) and contrasts them with the direct-input systems represented by agricultural and urban soils. Third, it documents the methodological heterogeneity of the underlying literature (differences in sampling depth, extraction protocols, identification techniques and particle-size thresholds) as a primary obstacle to mechanistic comparison and quantitative risk assessment. Together, these contributions clarify which patterns are robust across studies and which apparent differences are likely to be artifacts of methodology, thus providing a structured starting point for targeted future research.

MP characteristics, including size, shape and polymer type, are critical in determining bioavailability and potential impacts on soil microorganisms and ecosystem processes. Larger particles tend to accumulate in surface layers, whereas smaller particles (<250 µm) can penetrate deeper layers and interact with biota. Evidence also shows that certain polymers, such as PET, may reduce microbial diversity, while high concentrations can alter community composition and potentially affect nutrient cycling and soil ecosystem stability. These findings suggest that MPs in soils are largely secondary in origin, resulting from fragmentation and redistribution processes, and underline the need for systematic monitoring and categorization of soils to assess MP type, concentration and potential impacts. Beyond that, effective strategies should focus on prevention and sustainable land management practices, such as reducing polymer use to protect soil health and ensure the sustainability of terrestrial ecosystems.

Even finding alternative materials to replace plastics and reducing their production requires further attention. Without immediate action, plastic pollution will increasingly threaten terrestrial ecosystems, human health and sustainable land use. Future research should focus on standardized analytical methods, controlled experiments to clarify causal mechanisms, toxicity assessments of specific polymers and long-term monitoring in different land-use systems. However, the uneven geographical distribution of existing studies may limit the global representativeness of current knowledge, highlighting the need for more cross-regional investigations. Addressing these gaps will support effective policies, practical solutions and sustainable strategies for mitigating soil pollution from MPs.

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