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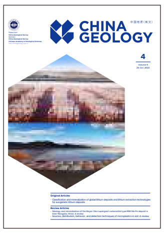

# Sources, distribution, behavior, and detection techniques of microplastics in soil: A review

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ABSTRACT

In recent years, the problem of environmental pollution caused by microplastics has attracted widespread attention. This paper reviews the latest research progress in terms of the source, content and distribution characteristics, harm, and detection technology of soil microplastics by referring to the relevant literature on soil microplastics worldwide. It concludes that: (1) Existing studies worldwide have detected the presence of microplastics in soil, water, and atmosphere, and the use of agricultural films, sewage sludge, and other man-made activities are the main sources of microplastics in soil; (2) microplastics can adsorb heavy metals, persistent organic pollutants and antibiotics in soil, change the physical and chemical properties of soil. This will result in composite pollution and harm to the ecosystem; (3) microplastics in soil not only can destroy the activity of key soil microorganisms, but also enter the body of crops and soil animals, affecting normal growth of crops and soil animals, and further threaten human health; (4) at present, there is no unified operating standard for the sampling, processing, and detection process of microplastics. Analysis methods such as visual inspection, spectroscopy, and thermal analysis have both advantages and disadvantages, and emerging detection technologies require urgent development. Microplastics have become a new pollutant in soil and their distribution characteristics are closely related to human activities. They pollute the environment and threaten human health through the food chain. Although related research on soil microplastics has just begun, it will become the focus of research in the future.

## 1. Introduction

Plastics have stable properties and are extremely difficult to completely degrade. After various natural actions, such as weathering, light, and radiation, they decompose to form plastic fragments with a particle size of <5 mm. It was first proposed by Thompson RC et al. (2004) for plastic debris in the marine environment. Studies on microplastic pollution have mostly focused on the water environment (Wang FT et al., 2022; Xiong W et al., 2022), while the soil environment has started relatively late. In 2012, Rillig MC (2012) first proposed that microplastics might harm the soil environment. Considering the close relationship between soil and food production and human health, research on soil microplastics has become a hot topic.

The cleavage of residual agricultural films is the most important source of soil microplastics. In addition, sewage sludge discharged from sewage treatment plants, degradation of plastic waste in landfills, and atmospheric deposition are important sources of soil microplastics (Kumar M et al., 2020). Microplastics can also affect the survival of soil animals, such as earthworms, the activity of some microorganisms, and even enter the food chain, causing harm to the ecological environment and human health (Zhu FX et al., 2019).

In the face of microplastics, a new type of pollutant, the United States started to ban the production and sale of cleaning cosmetics with plastic microbeads in 2015(Auta HS et al., 2017). Canada, France, the United Kingdom, Sweden, South Korea, New Zealand, and other countries have also gradually banned the production or sale of personal care products containing plastic microbeads. In recent years, China has also attached great importance to plastic pollution and has controlled it from the main sources of microplastics in

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farmland. However, China has not yet developed a monitoring system for microplastic pollutants, and relevant monitoring standards, laws, and regulations have yet to be established and improved.

To date, there have been few experimental studies on soil microplastics, and research progress has been slow. In this paper, the current research results on microplastics in soil were summarized, and the content and distribution characteristics of microplastics in the main environmental media at home and abroad, the main sources of microplastics in soil, the impact of soil microplastics on the ecological environment, and the enrichment risk in the food chain were analyzed. Finally, in view of the detection technology of soil microplastics, spectral and thermal analysis techniques that are currently widely used are introduced, with the aim of being helpful for further research in this field.

## 2. Microplastics in the Environment

### 2.1. Basic characteristics of microplastics

The main characteristics of microplastics include their functional groups, size, color, and shape. Common plastic structures include hydroxyl, carboxyl, ester, ether bond. Some also contain halogen, allyl and so on. The existence of different functional groups makes different types of plastics have their own characteristics. The size of microplastics is between 100 nm and 1 μm, and their color varies. Based on their shapes, they can be called films (Fig. 1a), pellets (Fig. 1b), fragments (Fig. 1c), foams (Fig. 1d), and fibers (Fig. 1e).

The degradability of plastics is related to multiple factors, such as plastic type, shape, and environment, and can be cleaved into microplastics through thermal degradation, biodegradation, photodegradation, and other methods. Studies have shown that plastics are most easily degraded in air (Cai LQ et al., 2018), and very slowly under the ultraviolet radiation (Tribedi P and Dey S, 2017). The aging comparison of the three common microplastics are listed in Fig. 2.With the development of technology, biodegradable plastics are available, which can be eventually degraded into water and carbon dioxide during the industrial composting process. Biodegradable plastics are expected to replace traditional plastics to reduce “white pollution”. However, biodegradable plastics still face problems such as high cost and difficulty in promotion.

### 2.2. Content characteristics and distribution of microplastics in soil

At present, most studies on microplastics focus on the water environment; however, He DF et al. (2018) reported that the content of microplastics in soil environments is markedly higher than that in water environments. Once microplastics enter the soil environment, they become increasingly enriched, making the soil environment a huge “warehouse” of microplastics.

Table 1 list the research results for microplastics in soils of different land types, such as cultivated land and industrial land in different locations. Owing to the different sampling methods and measurement techniques used in each study, the measurement units used in the research results were different, which mainly included three types: items/kg, particles/m$^2$ and mg/kg. By comparison, it is not difficult to find that there are orders of magnitude differences in soil microplastic content in different regions, ranging from one microplastic fragment in 3 kg soil to nearly 70000 microplastic fragments in 1 kg soil.

As can be seen from Table 1, no matter what type of land, there are generally microplastics in soil. The types of microplastics in farmland are mainly polypropylene (PP), polyethylene [including low density polyethylene (LDPE) and high-density polyethylene (HDPE)], and polystyrene (PS). Polyethylene succinate (PES) and polyvinyl chloride (PVC) are present in some soils. In addition, Corradini F et al. (2019) found acrylic and nylon fibers in farm soil samples from

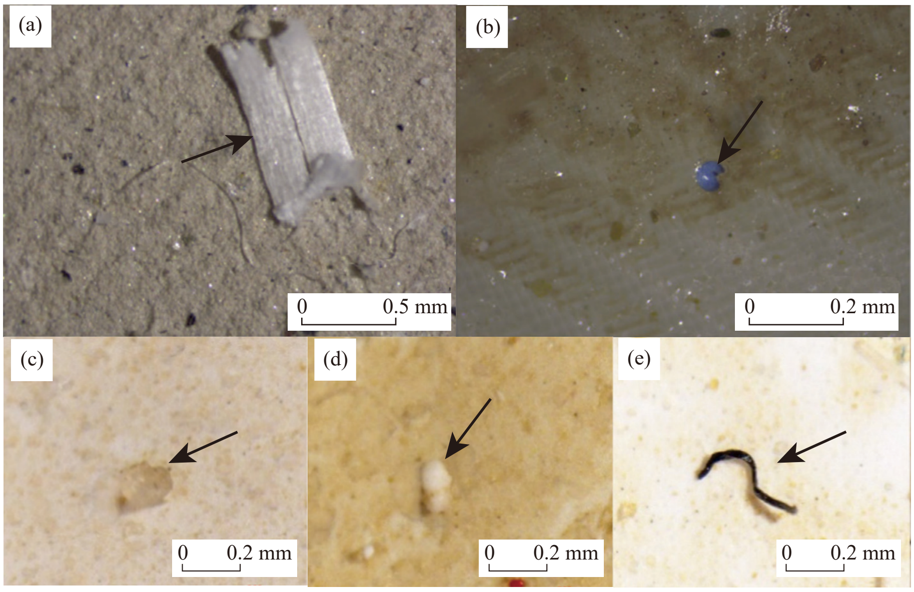

**Fig. 1.** Five common microplastic forms (a, b modified from Liu MT et al., 2018, c, d, f modified from Zhou YF et al., 2019) .

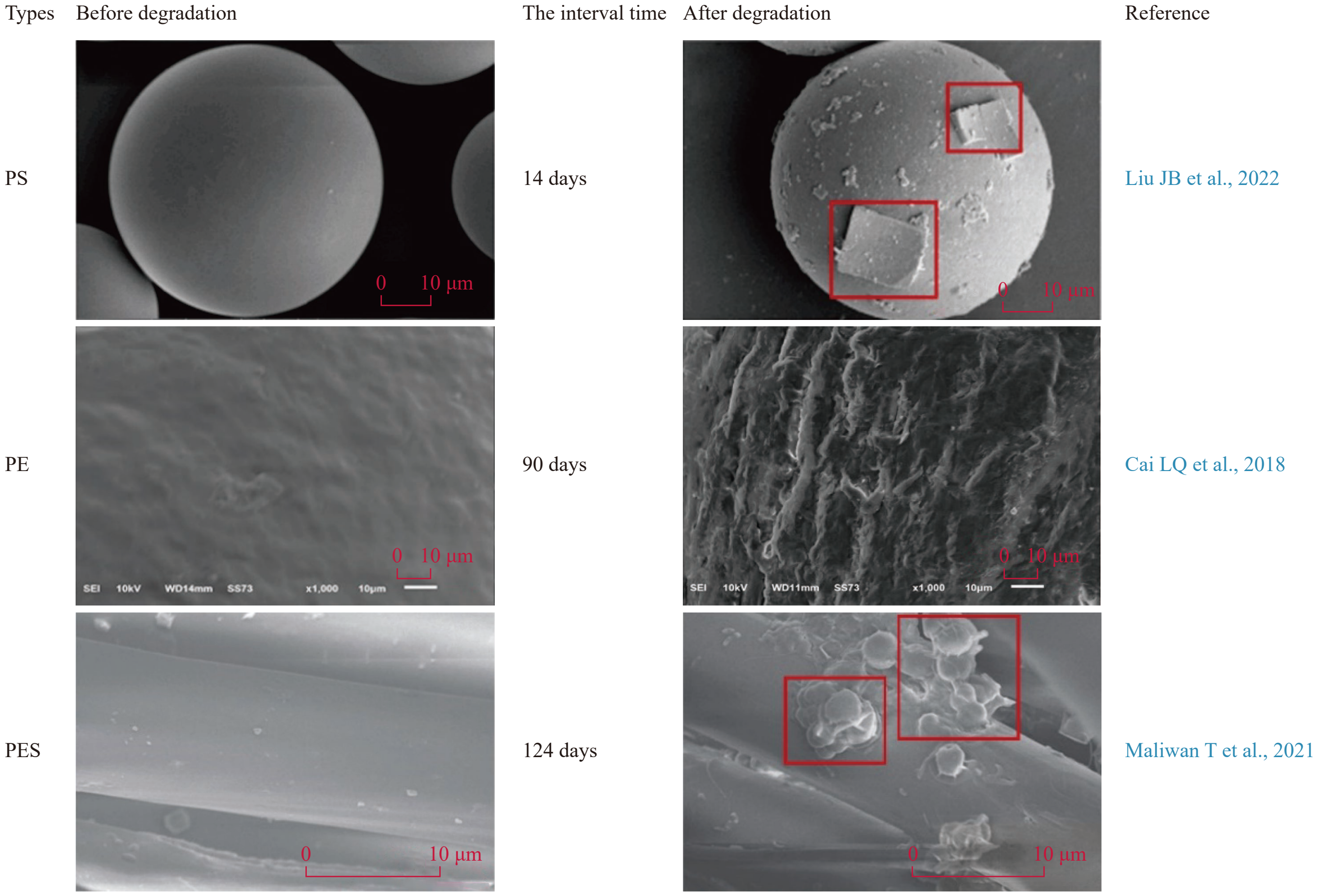

**Fig. 2.** Comparison of degradation of some microplastics (PS, PE and PES) .

Melipilla, Chile. Crossman J et al. (2020) found acrylic, polybutanediol terephthalate, and polyvinyl chloride acetate in farmland soil samples from Andarillo, Canada. Ding L et al. (2020) found polyethylene terephthalate (PET) in soil samples from Shaanxi Province.

Most of the microplastics in soil have small particle sizes (<1 mm). Microplastics are very rich in color. The most common are white and black, but also exist like blue, green, yellow, red and so on. Microplastics in farmland soil are typically in the form of fibers, films, pellets, and fragments. Foamy microplastics are rare. In addition, it can also be observed in farmland soil samples in the Fenhe and Hetao areas of China that the surfaces of microplastics have different degrees of damage, individual edges are rough, and pores exist (Wang ZC et al., 2020a; Zhu YE et al., 2021), and tend to further decompose into smaller microplastic fragments.

There are few studies on the distribution characteristics of microplastics in soil, but a number of studies have shown that the distribution characteristics of microplastics are different in farmland and other land types. Soil depth has a significant impact on the content of microplastics in soil, and the content decreases with increasing soil depth (Liu MT et al., 2018; Wang ZC et al., 2020a; Song DX et al., 2021). In addition, the particle size of microplastics in farmland soils is related to time and depth. Wang ZC et al. (2020a) demonstrated that the particle size of microplastics decreases over time. Liu MT et al. (2018) pointed out that the particle size of microplastics lessens with increasing soil depth. For cultivated areas, the use of agricultural plastic films affects the content of soil microplastics. Zhou B et al. (2020) found that in the same area, the content of soil microplastics in the mulched farmland was more than twice that in the non-mulched farmland.

For industrial land, Fuller S and Gautam A (2016) took 17 samples in Sydney, Australia. They found that microplastics in the soil reached 67500 mg/kg, and their distribution was mainly influenced by the surrounding industrial area. The distribution of microplastics in the soil of the Swiss floodplain is related to the level of urban development, and the more people living nearby, the higher the content of soil microplastics (Scheurer M and Bigalke M, 2018). The amount of microplastics in the soil of Kenilworth Park and Aquatic Gardens in Washington, United States is related to vegetation, with more lush areas having lower levels (Helcoski R et al., 2020). Algae has been found on the surface of microplastic samples from beaches along China's Bohai coast, which is believed that the distribution of microplastics in beach soil is closely related to the ebb and flow of the tide (Zhou Q et al., 2018). At present, the sampling methods and extraction methods used in different soil microplastic studies have not been standardized, and the units used in different experiments are also different. Therefore, a direct comparison of soil microplastic abundance values in different regions can provide limited information. Either the microscopic observation method or the method of screening microplastics

**Table 1. Content characteristics of microplastics in soil.**

| Location | Land type and crops | Types of Microplastics | Size | Content | Color | Shape | References |
|---|---|---|---|---|---|---|---|
| Franconia (Germany) | Farmland (Barley) | PE (62.50%), PS (25%), PP (12.5%) | 1–5 mm | Mean abundance 0.34±0.36 particles/kg | white (32.10%), transparent (20.99%), and blue (18.52%), and others | Flms (65.43%), fragments (25.93%), and others | Piehl S et al., 2018 |
| Mellipilla (Chile) | Farmland (Corn) | Acrylic, PES, Nylon, LDPE, PVC | <5 mm | 600–10400 particles/kg | / | Mostly fibers, but also films, fragments and pellets | Corradini F et al., 2019 |
| Valencia (Spain) | Farmland (Olive and Cereal) | PP, PVC | Most are between 150–250 µm | 930 ± 740 per/kg (light density MPs) and 11100 ± 570 per/kg (heavy density MPs) | / | Mainly fragments, followed by fibers and films | van den Berg P et al., 2020 |
| Ontario (Canada) | Farmland (Unknown) | PP, PE, PES, Acrylic and others | <5 mm | Average 541 per/kg | / | Mainly fibers, but also fragments | Crossman J et al., 2020 |
| Fen river coast (China) | Farmland (Unknown) | PE, PP, PS | 0.02–1 mm | Average 290.5±15.1 items /kg | Mainly white, color is very rich | Fibers accounted for the largest proportion of 52.67%, followed by films and fragments, foams is very little | Zhu YE et al., 2021 |
| Baoji (China) | Farmland (Kiwi, chili and corn) | / | <1 mm (41%–48%), followed by 1–2 mm and 2–5 mm | 1974–3656 items /kg | Black (78%), white (21%) and a few blue | Films and fragments mainly (70.6%–85.7%), the rest of the pellets, fibers, etc | Song DX et al., 2021 |
| Hetao region (China) | Farmland (corn and sunflower) | / | Most < 3 mm | Average 4316 items /kg | Black and transparent mainly, but also green, red, blue | Fibers(23.34%), fragments(26.31 %), films(37%), pellets(11.78%) | Wang ZC et al., 2020a |
| Nanjingand Wuxi (China) | Farmland (Vegetable, Bamboo, Tea) | PE, PP | 0.02–0.25 mm at most | 420–1290 items/kg | White is the most common, followed by blue and red, with black, yellow and green less common | Mainly fibers, but also fragments, and bulks | Li QL et al., 2019 |
| Shanghai (China) | Farmland (Vegetable) | PP(50.51%), PE(43.43%), PES(6.06%) | 0.03–5 mm, most < 1 mm | 78.00±12.91 items/kg | More black and transparent, less green and red, and less blue | Mainly fibers, but also fragments, films, and pellets | Liu MT et al., 2018 |
| Hangzhou Bay (China) | Farmland (rice, corn or sorghum) | PE, PP, Nylon, Polyester, Rayon, Acrylic, PA | 60 µm–5 mm | Average 503.3 pieces /kg | / | Fragments > fibers > films | Zhou BY et al., 2020 |
| Shaanxi (China) | Farmland (Unknown) | PS, PE, PP, HDPE, PVC and PET | 0–0.49 mm is the most (81%), and the rest for 0.5–5.00 mm | 1430–3410 items/kg | / | Fibers (49%), films (23.8%), fragments (21.9%) and pellets (5.07%) | Ding L et al., 2020 |
| Yunnan Lake (China) | Farmland(vegetable) | / | 0.05–1 mm (95%) | 7100–42960 particles/kg(Average 18760 particles/kg) | / | Fibers (92%), films (4.0%) and fragments (3.7%) | Zhang GS and Liu YF, 2018 |
| Sydney (Australia) | Industrial site | PE, PS, PVC | <1 mm | 300–67500 mg/kg | / | / | Fuller S and Gautam A, 2016 |
| Swiss | Floodplain | PE, PVC, PS, Latex | 88% is between 125–500 µm | 55.5 mg/kg | / | / | Scheurer M and Bigalke M, 2018 |
| Campeche (Mexico) | Gardens | / | <20 µm (59%), 20–50 µm (34%), >50 µm (5%) | 870±1900 particles/kg | / | / | Huerta LE, et al., 2017 |

**Table 1 (*Continued*)**

| Location | Land type and crops | Types of Microplastics | Size | Content | Color | Shape | References |
|---|---|---|---|---|---|---|---|
| Washington (USA) | Wetland Park | PS(29%), PE and synthetic rubber(8%), cellophane(6%), PP(4%), PET(3%), and others | 75 µm–5 mm | 7,387–47,047 items/m$^2$ | / | Fibres (77%–94%) and fragment | Helcoski R et al., 2020 |
| The Bohai Sea coast (China) | Beach | PE, PP, PS, polyether urethane and a polymer blend of both PE and PP | <1 mm (60%) | 1.3-14712.5 items/kg | / | Foams, pellets, fragments, flakes, fibers, films and sponges | Zhou Q et al., 2018 |
| Wuhan (China) | Woodland | Mainly PE, but also PP, PS, PA, PVC and others | 10–50 µm (46.1%), 50–100 µm (35.3%), 100–500 µm (18.1%), 500 µm–5 mm (0.2%) | $9.6\times10^4$–$6.9\times10^5$ 5 particle/kg | / | Fragments (52%), bead (14%), fibers (13.8%), foams (9.7%), films (1.6%) | Zhou YF et al., 2019 |
| | Vacant land | | | $2.2\times10^4$–$2\times10^5$ particle/kg | | | |

using a specific size will bias the results, leading to the observation of larger microplastics. This makes the results of microplastics abundance values lower than the actual environment (Piehl S et al., 2018; Corradini F et al., 2019).

### *2.3. Content characteristics and distribution of microplastics in other media*

Once in the ecosystem, microplastics migrate through different media and enter the soil. So the content and distribution characteristics of microplastics in water and atmosphere are also worthy of attention.

#### *2.3.1. Rivers*

In the past decade, there have been many studies on microplastics in rivers, and microplastics have been found in almost all investigated rivers. Table 2 lists the survey results for several rivers. Some of the results used different units of measurement, mainly items/L (or n/L or particles/m$^3$) and items/m$^2$. By comparison, it is not difficult to find that there are orders of magnitude differences in the content of microplastics in different rivers.

The most common types of microplastics are PE, PP, PS, PET and PVC. Polyamide (PA) is also present in Jinjiang River, and rivers of the Qinghai-Tibet Plateau (Jiang C et al., 2019; Liu YC et al., 2022). In addition, 30 different types of polymers were found in the Nakdong River, South Korea. Similar to the particle size characteristics of microplastics in soil, the particle size of microplastics in most water is <1 mm, which is consistent with the fact that the larger the particle size, the lower the microplastic content (Eo S et al., 2019). Microplastics are mainly composed of fibers, fragments, films, and pellets. The difference is that, although the proportion of foam-like microplastic samples is low, they are more common in water than in soil. In terms of color, microplastic samples in water are black, transparent, white, red, green, blue, and other rich colors; however, because of the aging and fading of microplastics or that colored microplastics are more likely to be eaten by animals in water (Xu P et al., 2019), transparent microplastics tend to account for a higher proportion. In addition, in the samples from the Weihe River, it was observed that the surface of microplastics had weathering characteristics such as rupture, wear, and porosity, and even small particles attached to the surface of microplastics could be observed (Ding L et al., 2019; Zhang QJ et al., 2021).

The spatial distribution of microplastics is significantly different in rivers. the microplastic content of rivers flowing from rural to urban areas has a gradually increasing trend, and the more densely populated areas and agricultural planting areas have higher microplastic content (Yonkos LT et al., 2014; Ding L et al., 2019). In addition, previous studies have confirmed that the content of microplastics is higher in rivers during the rainy season (Yonkos LT et al., 2014; Eo S et al., 2019). Considering that water has a strong transport capacity for microplastics (Ding L et al., 2019; Jiang Y et al., 2020), there is a risk of long-distance migration of microplastics along rivers.

#### *2.3.2. Sewage and sludge*

Wastewater from sewage treatment plants includes both domestic and industrial wastewater. Microplastics in domestic wastewater mainly come from microplastic particles in daily cleaning products and microfibers of chemical fiber clothing, while microplastics in industrial wastewater are mostly produced by industrial production activities, such as that of garment factories (Murphy F et al., 2016; Salvador CF et al., 2017). There are three types of sewage treatment technology. The primary treatment is physical treatment, including grilles, sedimentation tanks, etc., used to remove particles and sediments from sewage. The secondary treatment is mainly chemical treatment, using flocculation, oxidation and other ways to treat sewage, so that the content of harmful elements and organic pollutants in the treated sewage can reach the discharge standard. The tertiary treatment is biological

**Table 2. Content characteristics of microplastics in some rivers and lakes.**

| Rivers (lakes) | Types of Microplastics | Size | Content | Color | Shape | References |
|---|---|---|---|---|---|---|
| Yangtze estuarine (China) | / | 0.51–6.29 mm (Mean value: 0.90±0.74 mm) | 0.5–10.2 n/L | Transparent (58.9%), coloured (26.1%), white (8.7%), black (6.2%) | Fibres (79.1%), Films (9.1%), Granules (11.6%), Spherules (0.2%) | Zhao SY et al., 2014 |
| Yellow River (China) | PE, PP, PS, PET, and PVC | / | Average 5.358–654 n /L | Transparent, white, colored, and black | Fragments, foams, films, fibers, and particles | Liu RP et al., 2021a |
| Weihe River (China) | PE, PVC and PS | <0.5 mm (40.8%–68.8%), 0.5–1 mm (8.35%–24.2%) | 3.67–10.7 items/L | / | Fibers (38.25%–61.95%), fragments (10.6%–21.7%), pellets (0.4%–7.8%), films (17.4%–38.2%) and foams (0.25%–3.5%) | Ding L et al., 2019 |
| Buqu River, Naqu River, Brahmaputra River and two tributary of it (China) | PET, PE, PP, PS, PA | <1 mm exceeds 70% | 0.48–0.967 items/L | Transparent is the most common and also come in blue, black, white, red and green | Fiber is the largest, fragments and pellet are smaller | Jiang CB et al., 2019 |
| Jinjiang River Basin (China) | PE (57%), PP (23%), PVC(7%), PET(7%), PA(4%), PS(3%) | <100 μm (45%), 150–500 μm (44%), > 500 μm (11%) | 0.5–4 n/L | / | / | Liu YC et al., 2022 |
| Nakdong River (Korea) | PP (41.8%), PES (23.1%), PE (9.4%), PA (5.8%), PS (2.1%), alkyd (4.2%), acrylic (3.2%), poly (ethylene-vinyl acetate) (2.6%), polyurethane (1.4%), PVC (1.1%), and poly(acrylatestyrene) (1%), others | Mostly 50–150 μm | 0.293–4.76 particles /L | / | Fragment (69%), fibers (30%), spheres and films (1%) | Eo S et al., 2019 |
| Patapsco (USA) | / | 0.3–5.0 mm (0.3–2.0 mm is more common) | 59782±27323–297927±180252 pieces/km$^2$ | / | Fiber, film, fragment, pellet and foam | Yonkos LT et al., 2014 |
| Rhode (USA) | | | 18574±13347–131978±118895 pieces /km$^2$ | | | |

treatment, using biological nitrogen and phosphorus removal methods, activated carbon adsorption methods, etc., through biodegradation technology to further treat substances that are difficult to degrade or remove in the secondary treatment. The tertiary treatment can further treat substances that are difficult to degrade or remove from the sewage after secondary treatment. General sewage treatment plants have primary and secondary treatment capacities, and some also have tertiary treatment capacities. Comparing the different sewage treatment plant's ability to remove microplastics (Table 3), after tertiary treatment of domestic sewage, the water removal rate of microplastics is between 60% and 80%, and the removal rate of some European and American sewage treatment plants can reach >98% of plastic materials. Almost all sewage treatment plants have one thing in common: the primary treatment process based on physical treatment plays the most important role in the removal of microplastics, whereas the tertiary treatment process based on biological treatment has no obvious effect on the removal of microplastics (Carr SA et al., 2016; Mason SA et al., 2016).

Table 3 compares the content characteristics of microplastics in the inlet and output waters of several countries' sewage treatment plants. Among them, the inlet water of sewage treatment plants in Shanghai, China has the highest content of microplastics (226.27 n/L), while Sydney, Australia has the lowest content (2.2 n/L). The microplastic content per liter of effluent in most sewage treatment plants is <1/L, but still higher than that in natural water (Li XW et al., 2018). Sludge is produced by sewage through sedimentation treatment and other processes; therefore, the higher the removal rate of sewage microplastics, the higher the content of microplastics in the sludge output (Gies EA et al., 2018).

Li XW et al. (2019) noted that more than 30 types of microplastics such as PE, PES, PET, and PA were detected in the influent of the sewage plant. PE is most commonly found in personal care items, whereas PES, PET, and PA are more commonly found in clothing. In terms of shape, the main forms of microplastics in sewage are fibers and pellets, which are more common in clothing and personal protective products, respectively. In terms of color, transparent microplastics generally accounted for a high proportion of influent samples. In addition, colored microplastics could also be observed. The content of differently colored microplastics is closely related to the use habits of plastic products in the source area of sewage. Similar to the particle size characteristics of microplastics in water, microplastics in sewage are relatively small, with most microplastics in the size range of 50–100 μm. Microplastics removed by sewage sedimentation and other purification treatments enter the sludge. Therefore, the shape, particle size, and color characteristics of the microplastics in the sludge are consistent with those of the sewage.

Chen Y et al. (2020) collected and compared the population number and influent microplastic content of several sewage treatment plant service areas at home and abroad and believed that the main factors affecting the content of microplastic in the sewage are related to the population number and the development level of the city. However, Long ZX et al. (2019) indicated that there is no strong evidence to prove the relationship between the content of microplastics in sewage influent and population density. They reported that the amount of microplastic-containing sewage produced per capita was relatively stable at a specific stage of economic development. The main influencing factor of influent microplastics content should be plastic-related industrial production activities.

### *2.3.3. Atmosphere*

Research on microplastics in the atmosphere has been conducted recently. At present, the units of measurement used for research results on microplastics in the atmosphere are items/m$^3$ or n/m$^3$ (Table 4). The content of microplastics in the atmosphere varies significantly, however, their shape, size, and color characteristics are similar (Rachid D et al., 2017; Zhou Q et al., 2017). Taking the study of Shanghai by Liu K et al. (2019) as an example, the content of microplastics in the air in Shanghai ranges from 0 n/m$^3$ to 4.18 n/m$^3$, and the microplastic samples <1 mm account for up to 87%, which are mostly black in color and fibrous in form. No foam or film microplastics were observed.

**Table 3. Comparison of microplastic removal capacity of wastewater treatment plants in different countries.**

| Place | Average microplastic content before water intake (n/L) | Average microplastic content after effluent (n/L) | Handling | Microplastic removal rate after primary treatment | Microplastic removal rate after secondary treatment | Microplastic removal rate after tertiary treatment | References |
|---|---|---|---|---|---|---|---|
| Shanghai (China) | 226.27±83.00 | 83.16±17.22 | Tertiary treatment | 49.72% | 62.64% | 63.25% | Jia QL et al., 2019 |
| Nanjing (China) | 4.2 | 0.9 | Tertiary treatment | / | 61.9% | 78.6% | Chen Y et al., 2020 |
| Australia | 2.2 | 0.28 | Tertiary treatment | / | / | 87.3% | Ziajahromi S et al., 2017 |
| UK | 15.70±5.20 | 0.25±0.04 | Secondary treatment | 78.3% | 98.4% | / | Murphy F et al., 2016 |
| Finland | 57.6±12.4 | 1.0 ±0.4 | Secondary treatment | / | 98.3% | / | Lares M et al., 2018 |
| Canada | 31.1±6.7 | 0.5±0.2 | Secondary treatment | 91.7% | 98.3% | / | Gies EA et al., 2018 |

**Table 4. Content characteristics of microplastics in the atmosphere in some areas.**

| Region | The sample type | Types of Microplastics | Size | Content | Color | Shape | References |
|---|---|---|---|---|---|---|---|
| Beijing (China) | Atmospheric suspended matter | / | / | 5700 n/m$^3$ | / | / | Li YW et al., 2020 |
| Shanghai (China) | Atmospheric suspended matter | PET, PE, PES, PAN, poly (N-methyl acrylamide), rayon, ethylene vinyl acetate, epoxy resin and alkyd resin | 23.07–9554.88 μm | 0–4.18 n/m$^3$ | Black (28%), blue (25%), red, transparent, brown, green, yellow, and grey | Fibers (67%), fragments (30%), pellets (3%) | Liu K et al., 2019 |
| Pearl River Estuary (China) | PM2.5 | PP, PET, PEP, PA | 288.2–1117.62 μm | 0.030–0.077 items /m$^3$ | Black, white, red, yellow, brown | Fibers | Wang XH et al., 2020 |
| South China Sea (China) | | PP, PET, PEVA | 286.10–1861.78 μm | 0-0.031 items /m$^3$ | Black, yellow, red | Fibers (75%), fragments (25%) | |
| East Indian Ocean | | PET, PP, PAN, PR | 58.59–988.37 μm | 0-0.008 items /m$^3$ | Yellow, black, blue | Fibers (80%), fragments (20%) | |
| Paris (France) | Atmospheric suspended matter | PP, PA, PE | 0–1650 μm | 0.3–1.5 n/m$^3$ | / | / | Rachid D, et al., 2017 |

Microplastics in the atmosphere are closely related to human activities, transportation, and industrial activities (Abbasi S et al., 2017), mainly through the incineration of plastic waste, drying of clothing, and wear of road tires. Common atmospheric microplastics are PET, PE, PES, PVC, and polyacrylonitrile (PAN). Different combinations indicate different sources of microplastics. For example, PP and PES materials may come from carpets and furniture (Oluchi M et al., 2020), whereas PAN materials may come from the textile industry (Liu K et al., 2019).

Wang XH et al. (2020) also detected microplastics in an oceanic atmosphere with little human activity. They compared the content of microplastics in the atmosphere of the Pearl River Estuary, the South China Sea, and the East Indian Ocean and concluded that the microplastics in the oceanic atmosphere may come from the neighboring continental air. A modeling analysis by Steve A et al. (2019) showed that the migration distance of microplastics in the atmosphere could reach 95 km. Therefore, microplastics detected in the polar regions and the Qinghai-Tibet Plateau, where there is less anthropogenic and industrial influence, are most likely to migrate through the atmosphere (Melanie B et al., 2019; Evangeliou N et al., 2020).

## 3. Sources of soil microplastics

As a type of polymer compound, plastic is widely used in packaging, agricultural production, construction materials and other aspects of daily life. In 2020, China's primary plastic production reached 105.422 million tons. The main sources of soil microplastics are landfill, farmland mulching, irrigation, sludge composting, and atmospheric settlement (Fig. 3).

### *3.1. Disposal of plastic waste*

The treatment method and recovery rate of plastic waste directly affect the amount and type of microplastics entering the soil, water, and atmosphere. At present, the main treatment methods for plastic waste are incineration and landfill. Hardly any European and American countries can recycle >50% of plastic waste packaging, and the recycling rate of plastic waste in most countries is relatively low (Tang GL et al., 2013). According to Roland G et al. (2017), from the 1950 s to 2015, the global cumulative production of plastic waste reached $63\times10^8$ t, of which approximately $8\times10^8$ t was incinerated, $49\times10^8$ t was discarded directly or buried in the natural environment, and only $6\times10^8$ t was recycled.

### *3.2. Farmland film covering*

The use of agricultural films can reduce the evaporation of farmland water, reduce the impact of weeds, pests, and diseases on crops, and effectively improve the quality and yield of crops (Zhang F et al., 2018; Ding F et al., 2019). Therefore, they are widely used in agricultural production. In 2013, the consumption of agricultural films in the United States was 650000 tons, and in 2014, the EU produced 1.326 million tons. In recent years, the research focus in the field of agricultural plastic film has shifted from improving crop yields to pollution caused by microplastics. This shift has decreased China's agricultural plastic film usage after an increasing trend (Fig. 4); however, in 2019, agricultural plastic film usage was more than 2.4 million tons.

The plastic film was mostly composed of PE and PVC, and the recovery rate was generally low. The residual agricultural film in the soil is decomposed into microplastic fragments under multiple conditions, such as ultraviolet light, wind, and microorganisms. Microplastics can be detected in the vast majority of fields covered with plastic films. Therefore, agricultural films are regarded as a major source of soil microplastics. Jin T et al. (2020) compared the recycling situation of waste agricultural film at home and abroad and concluded that the recycling rate of waste agricultural film in Sweden and Ireland was the highest, reaching 68% and 63%, respectively, while that in several Eastern European countries such as Bulgaria and Romania was almost zero. The main film-mulched areas in China are arid and semi-arid in

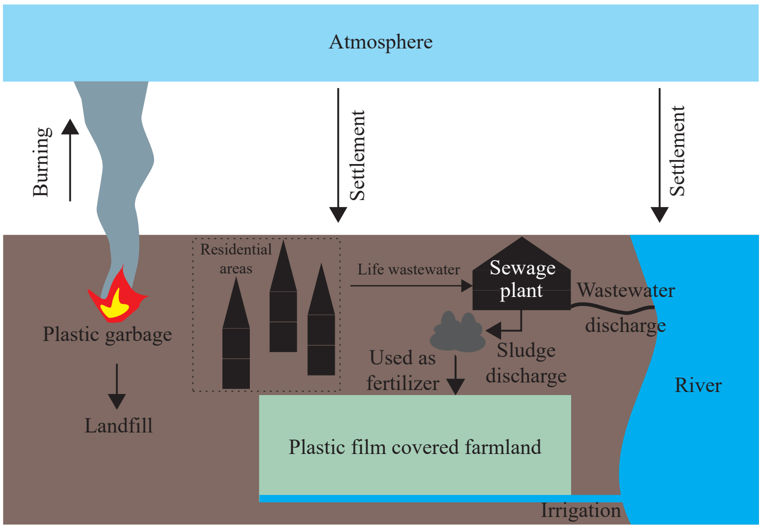

**Fig. 3.** Sources of microplastics in soil .

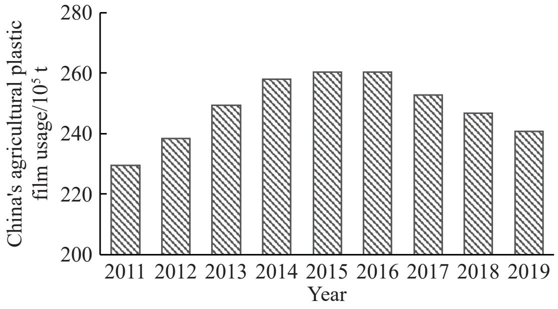

**Fig. 4.** Statistical chart of agrutural plastic film usage in China in recent years .

northwest China. With the attention of the state, agricultural film recycling demonstration zones have been established in Xinjiang, Gansu, and Inner Mongolia. The recovery rate of agricultural films in the zone can reach 80%, which is expected to increase.

### *3.3. Field composting*

Sludge contains N, P, K, and other nutrient elements that can improve soil fertility, therefore, it is often used as fertilizer in farmland. Nizzetto L et al. (2016) calculated that the direct application rate of farmland sludge in European countries ranged from 0% to 91%, and the average utilization rate was 43%.

Sludge is produced from sewage through sedimentation treatment and other processes; therefore, the higher the removal rate of microplastics in sewage, the higher the content of microplastics in the produced sludge. Corradini F et al. (2019) found in their study in Chile that the main shape of microplastics in farmland was highly similar to that in the sludge used, confirming that sludge application was an important source of microplastics in farmland soil. van den Berg P et al. (2020) showed in a study in Spain that the average content of microplastics in soil treated with sludge was 2–3 times higher than that in soil not treated with sludge. Zhang LS et al. (2020) compared orchard soils with different sludge application rates in Guilin, Guangxi, and found that the contents of microplastics in farmland soils with annual application rates of 30 tons/ha and 15 tons/ha were 545.9±45.7 and 87.6±9.3 n/kg, respectively. This value was considerably higher than that of farmland soil without sludge application (5.0±0.4 n/kg).

Data collected by Li PF et al. (2021) show that in 2017–2018, the EU produced approximately 44 million tons of sludge, and the United States produced approximately 38 million tons of sludge. Nizzetto L et al. (2016) estimated that, due to the application of sludge, approximately 63–430000 tons and 44–300000 tons of microplastics would be introduced into farmland soil in Europe and North America each year, respectively. According to the yearbook of the Ministry of Housing and Urban-Rural Development, the overall sewage treatment volume in China has shown an increasing trend in recent years (Fig. 5). For example, in 2020, the total amount of dry sludge produced by sewage treatment plants in urban and rural China was 13.33 million tons. According to 80% water content, the total output of sludge in the urban and rural areas of China in 2020 reached 66.65 million tons. According to the relationship between sludge production and soil introduction in Europe and the United States, it can be estimated that the annual introduction of microplastics into farmland soil in China is approximately 80000–520000 tons, which is extremely hazardous.

### *3.4. Farm irrigation*

Irrigation water containing microplastics will directly enter the soil. General agricultural irrigation water can be divided into two main types. One is surface water, mainly from rivers which is also the main irrigation water source for farmland. However, in arid and semi-arid areas with water shortages, sewage purified by sewage treatment plants will also be used.

Gatidou G et al. (2019) collected a large amount of data from sewage treatment plants in Europe, the United States, and Australia, and found that the amount of microplastics in raw sewage water was 1–3160/L and that in treated sewage was 0.0007–125/L. Although treatment significantly reduces the amount of microplastics in effluent water, long-term irrigation of farmland can still transfer a large amount of microplastics to the soil. Gies EA et al. (2018) investigated Vancouver's largest wastewater treatment plant and estimated that it could still inject 30 billion microplastic particles into the environment annually, despite removing 97–99% of microplastics from sewage. The annual sewage treatment volume in China showed an increasing trend from 2011 to 2020 (Fig. 5). In 2020, the volume of sewage treatment volume reached 5572782 million $m^3$. Owing to the large base, the emissions of microplastics should not be underestimated and should be taken seriously.

### *3.5. Atmospheric subsidence*

Microplastics in the atmosphere eventually settle to the surface and in water, which is an important source of microplastics in soil. The research results of Cai L et al. (2017) showed that the daily atmospheric deposition of microplastics in Dongguan (Guangdong, China) was 175–313 pieces/$m^2$, similar to Hamburg (275 n/$m^2$ on average), and lower than that of London (575–1008 n/$m^2$). The atmospheric

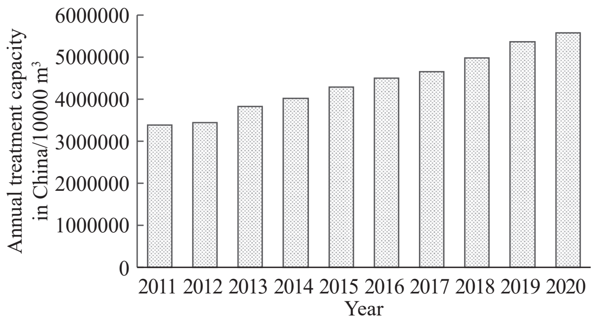

**Fig. 5.** Annual sewage treatment volume of China in recent years .

deposition of microplastics in these three cities include PE, PP, PS, PET, PVA, and PAN, most of which are smaller than 1 mm and mainly fibrous. Dris R et al. (2016) also found that the atmospheric deposition of microplastics in Paris was almost fibrous, with a daily deposition of 2–355 n/m$^2$. It has been estimated that the annual deposition of microplastics into the soil in Paris through atmospheric deposition could reach 3–10 t. Rachid D et al. (2017) showed that the sedimentation rate of plastics in the atmosphere was related to their size, and the larger the size of microplastics, the faster they would settle and aggregate on the soil surface. In addition, rainfall also can accelerate the deposition of atmospheric microplastics. However, there are few studies on microplastics in atmospheric deposition, and the migration mode and sedimentation amount of microplastics in atmospheric circulation require further exploration.

## 4. Microplastics and soil

Plasticizers, dyes, and other chemical additives are typically added during plastic processing. Under the action of weathering and light, the internal molecular bonds are broken and plastic is broken into microplastic particles (Liu R et al., 2021b), so that harmful substances in the additives are released into the soil. Cracked microplastics have a large specific surface area and the ability to adsorb different substances in the soil, resulting in soil pollution.

### *4.1. Effects of microplastics on soil physical and chemical properties*

The presence of microplastics in soil generally increases the size and number of soil aggregates, enhances the conductivity of water in the soil, and ultimately accelerates soil water evaporation. For example, de Souza Machado AA et al. (2019) found that the addition of 0.4% PES microplastics significantly changed the soil bulk density and the number of aggregates, thus significantly increasing the evaporation rate of soil water. The experimental results of Wan Y et al. (2019) showed that the size and concentration of microplastics were the main factors controlling the evaporation rate of soil water. The smaller the size and higher the content of microplastics, the higher the evaporation rate of water between the soil pores.

Residual microplastics in soil can change soil pH, electrical conductivity (EC), and other properties. For example, polylactic acid (PLA) and LDPE increase soil pH (Wang FY et al., 2020b). LDPE can reduce the soil EC value (Gong J and Xie P, 2020). Changes in pH, EC, and other properties can affect the ability of microplastics to adsorb pollutants, thus affecting the soil environment (Luo YY et al., 2020). However, some studies have shown that high concentrations of PP microplastics can reduce the decomposition rate of soil organic matter and increase the content of soil soluble organic matter (Liu HF et al., 2017), which may be beneficial for soil carbon storage. In addition, Song DX et al. (2021) found that the microplastic surface in soil samples adsorbed oxides of N and C, the main components of fertilizer, leading to local enrichment of the soil fertilizer, which was not conducive to crop growth.

### *4.2. Composite pollution of microplastics and pollutants*

The affinity between the functional groups of plastic surface and pollutants is an important mechanism of their interaction. For example, PS can be associated with organic compounds through π-π bonds (Mei WP et al., 2020), and PA is easy to adsorb pollutants through H bonds because it contains C-O bonds and N-H bonds (Song H et al., 2019). When the microplastic fragments formed after plastic cracking have strong hydrophobicity and a large specific surface area, they will become the transport carriers of harmful substances. Over time, the surface of fragmented microplastics will become increasingly rougher under various effects (Chai BW et al., 2021), and with increasing adsorption sites, the internal structure begins to change, and the adsorption capacity is enhanced.

The mechanism of action between microplastics and persistent organic pollutants is mainly on the van der Waals force, and the strength of adsorption capacity is closely related to the number of oxygen-containing functional groups on the surface of microplastics (Hüffer T et al., 2018; Xu ZL et al., 2020). Common persistent organic pollutants in the soil environment include polycyclic aromatic hydrocarbons and polychlorinated biphenyls, which are hydrophobic organic pollutants that are easily adsorbed by microplastics (Wan HY et al., 2022). Liu J et al. (2018) reported that the adsorption capacity of microplastics to organic pollutants is related to the polarity of pollutants, and nonpolar and weakly polar organic pollutants are more likely to migrate in soil under the action of PS microplastics. Hüffer T et al. (2019) showed that PE microplastics in soil can adsorb atrazine and 4-(2, 4-dichlorophenoxy) butyric acid, which reduces the ability of the soil to immobilize them and increases the risk of organic pollutants entering groundwater.

The adsorption of antibiotics by microplastics is mainly dependent on electrostatic force. In addition, H bonds is also an important factor affecting the adsorption capacity of microplastics to antibiotics (Zhang HB et al., 2018). Common antibiotics in soil include tetracycline, oxytetracycline, and amoxicillin. Yang J et al. (2019) conducted experiments on tetracycline in soil, and the results showed that the adsorption capacity of three types of microplastics for tetracycline in soil was PE > PS≈PA. Li J et al. (2021) confirmed that microplastic PA can act as a carrier to adsorb oxytetracycline in soil and enhance its migration ability.

Microplastics are easy to produce precipitation with heavy metal cations under the complexation, which makes microplastics directly adsorb heavy metals (Zou YJ et al., 2020). Wang F et al. (2020a; 2020b) conducted many studies on the interaction between soil microplastics and Cd, and the results showed that HDPE, PS, and PLA all adsorbed Cd in soil, reducing the soil's adsorption capacity for Cd. Moreover, Cd adsorbed by microplastics is easily desorbed, which leads to an increase in Cd bioavailability in the soil. PET microplastics can be used as carriers to migrate Cd, Pb, and Zn to the rhizosphere of wheat and desorb them (Abbasi S et al., 2020), proving that microplastics can simultaneously enhance the bioavailability of multiple heavy metals in soil. The adsorption capacity of microplastics for heavy metals is closely related to the degree of aging. Wang QJ et al. (2020) confirmed that the adsorption capacities of HDPE, PVC, and PS microplastics for Cu and Zn were enhanced after artificial aging.

Combining the pollution of microplastics and the above pollutants in soil, it can be found that microplastics can assist the downward migration of harmful substances and increase the risk of bioavailability of harmful elements (Fig. 6). However, most of the existing research results on the composite pollution of microplastics in soil were obtained using the laboratory control variable method. In a real and complex soil environment, the adsorption capacity of microplastics for pollutants is affected by soil pH, organic matter content, redox, and other physical and chemical conditions. This combined pollution mechanism requiresfurther exploration.

## 5. Influence of microplastics

Microplastics enter the soil and accumulate. They disturb the original order of animals and microorganisms in the soil environment. In addition, they can be absorbed into the body of crops and affect crop growth.

### *5.1. Microplastics and crops*

Several experiments have confirmed that smaller microplastics can enter crop cells from the external environment. Li LZ et al. (2020) cultured wheat with fluorescently labeled PS (0.2 μm and 2 μm diameter), and found that a 0.2 μm PS exists in the outer cortex of wheat root, which is transported to the aboveground part through xylem under transpiration, and finally reaches the stem and leaf, where the presence of PS microplastics can be detected in the leaf vein (Li LZ et al., 2020). Using a fluorescent labeling method, they also confirmed that 0.2 μm polymethyl methacrylate (PMMA) could enter the cells in lettuce roots, even into lettuce stems and leaves. In addition, microplastics can reduce the activities of key enzymes in the body of crops, affect the contents of photosynthetic pigments and soluble proteins in crops, damage the photosynthetic system of leaves, and hinder the synthesis of proteins, thus inhibiting crop growth and development.

It is generally believed that microplastics entering the roots of crops through the cell wall will cause damage to crops, however, the specific effects vary with the type, size, concentration, crop type, and growth stage of microplastics, as shown in Table 5. Lian YH et al. (2022) studied the difference between the effects of PE and PLA on soybean growth and found that PE had no significant negative effect on soybean growth, whereas PLA significantly reduced the root length of soybean. Jiang XF et al. (2019) confirmed that 0.1 μm PS could enter the root cells of Vicia faba, and when it accumulated to a certain extent, it blocked the cell wall pores and intercellular nutrient transport channels, and inhibited growth. The experimental results of Liao YC et al. (2019) showed that larger microplastics may hinder the normal growth and development of crops more than smaller microplastics. An J et al. (2021) used PVC-containing soil to grow post-seedling soybean plants and found that PVC microplastics significantly inhibited the leaf area, plant height, and root weight of soybean seedlings (within 14 days of emergence), however, this inhibition gradually diminished when plants reached 21 days of emergence. Qi Y et al. (2018)

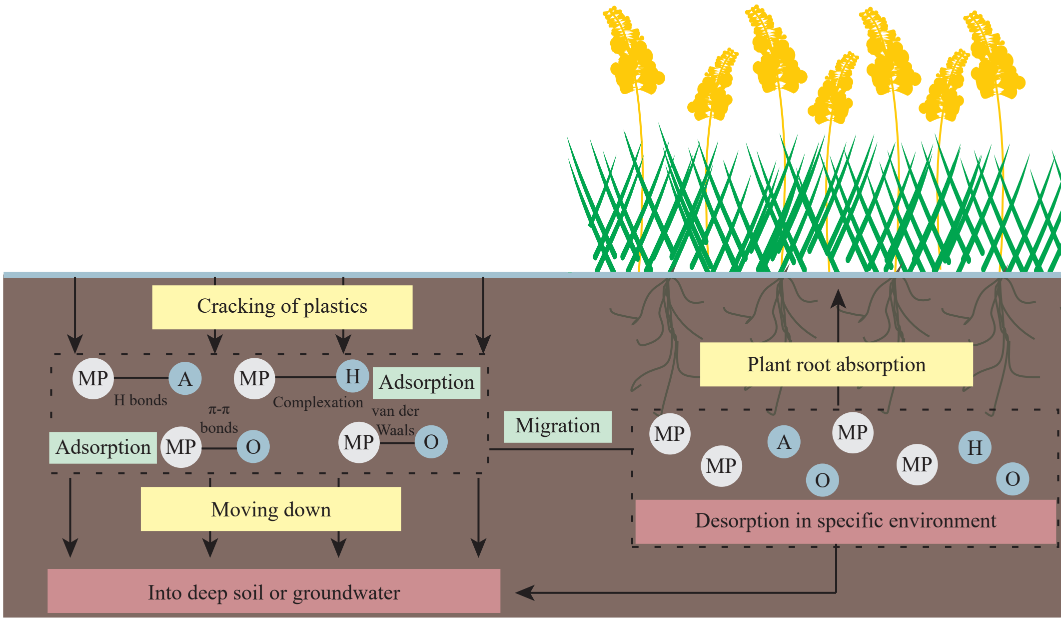

**Fig. 6.** Coexistence risk of soil microplastics and pollutants. MP–microplastics; A–antibiotics; H–heavy metals; O–organic pollutants.

**Table 5. Effects of different kinds of microplastics on plant growth of some crops.**

| Type of crop | Types of microplastics | The size and concentration of microplastics | Effects on crops | References |
|---|---|---|---|---|
| Wheat | PS | 100 nm and 5μm; hydroponics: 10, 20, 50, 100, 200 mg/L; soil culture method：1, 10, 50, 100 mg/kg | Hydroponics: At high concentration, the root length and stem length of wheat were significantly inhibited, and PS with lae particle size showed a stronger inhibitory effect; Soil culture method: The photosynthetic system of wheat leaves was damaged | Liao YC et al., 2019 |
|  | LDPE | 1 mm–500 μm, 500–250 μm, 250–50 μm; 1% | LDPE could inhibit the number and area of leaves | Qi YL et al., 2018 |
|  | PS | 100 nm; 5% | PS had no obvious effect on seed germination percentage, but could reduce root to shoot ratio of wheat seedlings | Lian J et al., 2020 |
| Lettuce | DBP and PE | 23 μm; 0.25, 0.5, 1 g/L | Both kinds of microplastics can inhibit lettuce’s growth, hinder photosynthesis and cause lettuce's stress response | Gao ML et al., 2019 |
| Spring onion | PA | 15–20 μm; 2% | PA could significantly inhibit stem length and root length, but it could significantly promote leaf mass | de Souzaahado AA et al, 2019 |
| Soybean | PE and PLA | PE：20–50 μm; PLA：20–60 μm; 0.1%, 1% | The root length of soybean was significantly reduced by PLA at 0.1% concentration, but not by PE | Lian YH et al., 2022 |
|  | PVC | <15 μm; 0.054, 0.54, 1.62, 2.70 g/kg | Medium and high concentration of PVC could significantly inhibit the leaf area and plant height of soybean seedlings, but the influence ability gradually decreased with the extension of time | An J et al., 2021 |
| Vicia faba | PS | 5 μm and 100 nm; 10, 50, 100 mg/L | 5 μm PS had no significant effect on broad bean. The presence of 100 nm PS in the root of Vicia faba could disrupt nutrient transport | Jiang XF et al., 2019 |

also showed that LDPE residue in soil could inhibit the leaves of wheat plants, however, this inhibitory effect would be alleviated in the presence of earthworms.At present, the effects of soil microplastics on crops are mostly obtained in laboratory experiments with control variables; therefore, whether the existing rules also exist in complex real environments requires further verification.

### *5.2. Microplastics and soil fauna*

The main consumers of soil are protozoa, such as ciliates, flagellates, and amoebas, which migrate surface microplastics into deeper soil through their activities in the soil, making microplastics more easily absorbed by crop roots. Numerous studies have shown that microplastics are easily ingested by soil animals because of their extremely small size (Rillig MC and Bonkowski M, 2018; Wang J et al., 2019), which also has a significant impact on the animals themselves (Table 6). Taking earthworms as an example, the activities of peroxidase and catalase were significantly enhanced, whereas the activities of superoxide dismutase and glutathione S-transferase were significantly decreased after ingestion of microplastics. This change in hormone levels demonstrates that earthworms developed a stress response to microplastics (Wang J et al., 2019). Song Y et al. (2019) found that snails ingest microplastics with smooth surfaces, however, microplastics in snail intestines and excreta become coarse, suggesting that snails can digest microplastics and even accumulate toxins. According to existing studies, microplastics can affect the normal growth and reproduction of soil invertebrates, such as earthworms, nematodes, and springtails, and may cause death in serious cases.

### *5.3. Microplastics and microorganisms in soil*

Different regions exist in different soil environments; therefore, microplastics have a different effect on soil microorganisms (Liu HF et al., 2017), however, most of the experiments show that the effects of microplastics are mostly negative (Table 7). On the one hand, abundant and diverse microorganisms increase the diversity of the ecosystem, however, microplastics can significantly change the community structure and diversity of arbuscular mycorrhizal fungi (Wang FY et al., 2020a). Therefore, microplastics can pose a threat to microbial diversity in soil. On the other hand, microplastics can affect the activities of key enzymes in soil, thereby reducing the recycling capacity of soil organic carbon, nitrogen, and other nutrients and affecting the growth of crops. Qian HF et al. (2018) suggested that the long-term application of PE film significantly inhibited soil urease activity and reduced soil organic matter and inorganic nitrogen content. Awet TT et al. (2018) found that dehydrogenase activities involved in N- (leucine-aminopeptidase), P- (alkaline phosphatase), and C- (β-glucosidase and cellobiohydrolase) cycles were significantly reduced, which affects soil nutrient content and is not conducive to crop growth. Many studies have shown that microplastic surfaces can adsorb microorganisms and form biofilms. If bacteria accumulate, they become harmful migratory bodies and destroy the original soil order (Richard H et al., 2019).

### *5.4. Microplastics and Human health*

Studies have suggested that microplastics can enter the body, however, there are minimal studies on this topic.

**Table 6. Effects of different types of microplastics on some soil fauna.**

| Animal species | Types of microplastics | The size and concentration of microplastics | Effects on animals | References |
|---|---|---|---|---|
| Earthworm | PS, PP, PET, LDPE | About 250μm irregular shape; 2.5%, 5%, 7% | The production of mucous in the epidermis of earthworms exposed to microplastics decreased and damaged the skin. Ingested microplastics are found throughout the worm’s body, mainly in the intestine | Baeza C et al., 2020 |
| | PES | The average length is about 361.6 μm and the diameter is about 40.7 μm; 0.1%, 1%, | Earthworms ingested with microplastics showed some emergency response, with a significant reduction in fertility at concentrations up to 1.0%, but no lethality was observed with ingestion | Prendergast-Miller MT et al., 2019 |
| Nematodes (Caenorhabditis elegans) | PS | 42 nm and 530 nm; 100 mg/L (liquid) and 10 mg/kg (soil) | Nematodes are more sensitive to microplastics with large particle sizes, and microplastics significantly reduce the number of nematodes’ progeny | Kim SW et al., 2020a |
| | HDPE, PET, PP, PS, LDPE and PAN | <250 μm, 250–630 μm, 630–1000 μm; 0.01%, 0.1%, 1% | Microplastics can reduce the reproductive capacity of nematodes | Kim SW et al., 2020b |
| Springtail (Folsomia candida) | PE | <50 μm, 50–200 μm, 200–500 μm; 0%, 0.005%, 0.02%, 0.1%, 0.5%, 1% | Springtail avoids soil containing microplastics; When the concentration of microplastics was 0.1%, the reproduction of springtail was inhibited, and when the concentration was 1%, the reproduction rate of springtail decreased to 70.2%. When the microplastic concentration was 0.5%, bacterial diversity in the springtail intestine decreased | Ju H et al., 2019 |
| Terrestrial snails (Achatina fulica) | PET | The average length was 1257.8 μm, and the diameter was 76.3 μm; 0.01–0.71 g/kg | Terrestrial snails intake of PET will appear stress response, resulting in lipid peroxidation, causing damage to the gastrointestinal tissue | Song Y et al., 2019 |

**Table 7. Harm of several common microplastics to soil microorganisms.**

| Type of microplastics | Concentration of microplastics | Effects on microorganisms | References |
|---|---|---|---|
| PE, PLA | 0.1%, 1% and 10% (w/w) | The community structure and fungi diversity of arbuscular mycorrhizal fungi (AMF) were significantly changed | Wang FY et al., 2020a |
| PE, PVC | 1% and 5% (w/w) | The activity of fluorescein diacetate hydrolase was inhibited, the activities of urease and acid phosphatase were stimulated, and the richness and diversity of bacterial communities were declined | Fei YF et al., 2020 |
| PVC | 0.1% and 1% (w/w) | The available P concentration was decreased, but the available N was not affected | Yan YY et al., 2020 |
| PS | 0.1 mg/kg and 1 mg/kg | Dehydrogenase activity and activity of enzymes involved in N-(leucine-aminopeptidase), P-(alkaline-phosphatase), and C-(β-glucosidase and cellobiohydrolase) cycles were significantly reduced, affecting soil nutrient content | Awet TT et al., 2018 |

Schwabl P et al. (2019) found an average of 20 microplastics per 10 g of human feces, ranging from 50 μm to 500 μm in size, with the highest levels of PP and PET. The latest research results of Leslie HA et al. (2022) confirmed the existence of microplastics in human blood, and the main types are PET, PE, and styrene polymers. This means that microplastics may pass through organs such as the biliary tract and kidneys in the blood circulation and end up in the human body.

Microplastics enter the body in two ways: either through respiration or through the food chain. Studies have shown that 26–130 microplastics can be inhaled into human lungs daily (Prata JC 2018). It is extremely difficult for human lungs to remove microplastics inhaled from the air, which can cause respiratory diseases such as asthma, chronic bronchitis, and pneumonia, and become one of the factors inducing cancer (Li YW et al., 2020). Huerta LE et al. (2017) identified a food chain (soil–earthworm–chicken) in which microplastics had an enrichment coefficient of 12.7 from soil to earthworm manure and up to 105 from soil to chicken manure. Humans at the top of the food chain are at high risk.

## 6. Analytical techniques for soil microplastics

At present, the analysis methods for microplastics in soil have not been standardized, particularly in complex soil environment samples, and the accurate analysis of microplastics has become concerning. At present, most research is divided into different steps: sampling, separation, extraction, and detection. The advantages and disadvantages of different separation and detection methods differ.

### *6.1. Extraction technology of microplastics*

The collected soil samples were passed through a 5 mm or 2 mm pore size sieve to remove larger particles and other impurities, and then the microplastics were extracted and separated. The soil environment is complex. To analyze microplastics in soil samples, it is necessary to separate microplastics from interfering substances, such as organic matter, and extract separate microplastics for qualitative and quantitative analyses.

### *6.1.1. Microplastic separation technology*

A key step in studying microplastics is separating them from the sample. The lower the amount and shape loss of the isolated microplastics, the higher the accuracy of the next microplastic identification. There are two main methods of microplastic separation: salt solution flotation and oil extraction (Table 8). The general extraction steps are illustrated in Fig. 7. However, the recoveries of microplastics using different methods were mostly obtained by simulating environmental samples in the separation experiment. Whether microplastics can be effectively extracted in complex environments is an urgent problem that needs to be solved.

The density of common microplastics is approximately 0.8–1.4 g/cm$^3$. The salt solution flotation method uses the density difference between microplastics and the soil to separate microplastics. The reagent used in the general salt solution flotation method to separate microplastics from soil is a saturated NaCl solution with a density of 1.2 g/cm$^3$. This reagent has a single, harmless composition and is cheap; however, it has a poor extraction effect on high-density polymers such as PVC and PET (Liu MT et al., 2018). For denser polymers, some researchers choose to use NaI solution (1.8 g/cm$^3$ density) or $ZnCl_2$ solution (1.6 g/cm$^3$ density) for separation (Van Cauwenberghe L et al., 2015; Li QL et al., 2019). The separation effect is good, however, the solution cost is high and pollutes the environment; therefore, the selection rate is not high. The NaBr solution (density 1.55 g/cm$^3$) and sodium polytungstate solution (density 1.4 g/cm$^3$) may be suitable alternatives. The NaBr solution is safe, affordable, and has the desired density. Sodium polytungstate solution can separate plastic particles from organic-material-rich samples (Okoffo ED et al, 2021).

The oil extraction method, first proposed by Crichton EM et al. (2017), takes advantage of the lipophilicity of plastics by replacing the salt solution in the flotation process with vegetable oil and then rinsing the oil with absolute ethanol. This method can avoid the influence of elements in salt solutions on the results of Raman spectroscopy analysis of microplastics to achieve the purpose of separating microplastics from soil. Thomas M et al. (2019) experimented with castor oil as an extractor and found average recoveries of up to 99% for PP, PS, and PMMA, but it was not sufficient for high-density microplastic polymers. Kim J et al. (2022) tried to use mineral oil instead of vegetable oil, and when using a polydimethylsiloxane-coated nickel (Ni) foam adsorbent on LDPE, PP, PS, PET, PVC and seven other microplastics, the recycling success rate was >99%.

### *6.1.2. Digestion*

Impurities such as organic matter in the sample will interfere with the identification of microplastics; therefore, it is necessary to use specific reagents to digest the sample and improve the accuracy of the subsequent detection of microplastics. Common digestion methods can be divided into acid, alkali, enzyme, and others (Table 9).

$HClO_4$ and $HNO_3$, which are oxidizable acids, are often used in acid digestion. For example, the International Council for the Exploration of the Sea suggests the use of $HClO_4$ and $HNO_3$ in a volume ratio of 1:4 for the digestion of marine animal tissues. HCl is rarely used alone owing to its poor digestion effect. Although acid has a good effect on organic matter digestion, it can be found from many studies on water environments that the use of the acid digestion method may damage microplastics (Catarino AI et al., 2017; Prata JC et al., 2019). In addition, the use of $HNO_3$ can also dye microplastics yellow (Dehaut A et al., 2016), thereby affecting the analysis results.

Alkali digestion mostly uses NaOH or KOH. This digestion method can be used to digest specific types of microplastics (such as PET, PC, and CA) (Dehaut A et al., 2016). The alkali digestion method is milder than the acid digestion method, the digestion effect is better, and its range of use is wider (Chen YL et al., 2022). Alkali digestion typically takes a long time and has a poor digestion effect on some types of organic matter in soil; therefore, it is unsuitable for complex soil environmental samples with high organic matter content (Hurley RR et al., 2018).

Enzymatic digestion is mostly used to separate microplastics from samples with a high biomass content. For example, the digestion rate of organic matter in water samples containing organisms reached 97.7% (Cole M et al., 2015).

**Table 8.** **Comparison of advantages and disadvantages of microplastics separation technology in soil.**

| Separation methods | Principle of separation | Advantage | Deficiency | References |
|---|---|---|---|---|
| Salt solution flotation method | Microplastics differ in density from soil | Most reagents are single, harmless and inexpensive | It is difficult to extract microplastics with large density differences with single reagent | Liu MT et al., 2018<br>Zhang SL et al., 2019<br>Okoffo ED et al, 2021 |
| Oil extraction method | Microplastics are lipophilic | The reagent composition is simple. No alcohol residue after cleaning. Follow-up tests are not affected | The extraction effect in soil needs to be further explored | Crichton EM et al., 2017<br>Kim J et al., 2022<br>Chen YL et al., 2022 |

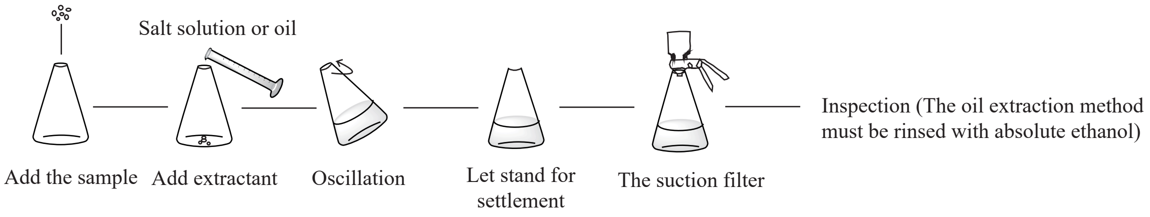

**Fig. 7.** Schematic diagram of extraction steps of microplastics (modified from Dong MT et al., 2020) .

**Table 9. Comparison of the four digestion methods.**

| Digestion method | Reagent | Dispelling effect | Applicable sample type |
|---|---|---|---|
| Acid digestion | $HNO_3$; HCl; $HClO_4$ | $HNO_3$ has the strongest digestion ability for organic matter, but it may destroy microplastics and affect the color of microplastics. HCl and $HClO_4$ are mostly used in mixed acids, not individually. | Sediment; soil; water; organisms |
| Alkali digestion | NaOH and KOH | They are relatively mild, but the decomposition ability of humic acid is weak, and the digestion time is long, and it is possible to eliminate specific types of microplastics. | Organisms; water |
| Enzyme digestion | According to the sample flexible collocation, such as Proteinase-K | Does not affect microplastics, but requires a long time and high cost of support, and the scope of application is very narrow | Organisms |
| Others | $H_2O_2$, Fenton, $KMnO_4$ and $K_2Cr_2O_7$ | They can effectively remove organic matter, have less impact on microplastics, and are cheaper and faster. The utilization rate of $H_2O_2$ and Fenton is higher. | Sediment; soil; water; organisms |

However, for a complex soil environment, many experiments are needed to select an enzyme type with high digestion efficiency, and the specific enzyme digestion method in a certain area is difficult to be universal. Therefore, whether the enzyme digestion method can be widely used to separate microplastics in soil environments requires further exploration.

The most common reagent used in other methods is $H_2O_2$, however, potassium permanganate and potassium dichromate are also used in a few cases. $H_2O_2$ can effectively remove organic matter from soil samples, although it can also decompose trace microplastic samples (for example, $H_2O_2$ can degrade PE and PP; Nuelle M et al., 2014). However, Wang ZC et al. (2020b) reported that using 30% $H_2O_2$ is one of the best digestion methods to minimize the mass change of microplastics and has little influence on the surface shape and the corresponding elemental composition of microplastics. Yu GB et al. (2017) compared the digestion ability of potassium permanganate and potassium dichromate on sugarcane field samples rich in organic matter. The results showed that 0.4 mol/L potassium permanganate had the best ability to remove organic matter from soil samples under acidic conditions, and the removal rate was >90%. Fenton's reagent is an oxidizing agent comprising ferrous ions and $H_2O_2$. Hurley RR et al. (2018) compared the digestion effects of the alkali digestion method (NaOH and KOH) with Fenton's reagent and found that Fenton's reagent had better digestion effects on organic matter. It is effective, inexpensive, and worthy of popularization.

## *6.2. Detection technology of microplastics*

Common detection methods for soil microplastics generally include visual inspection, spectroscopic methods, and thermal analysis technology. The advantages and disadvantages of each method are shown in Table 10. However, there is no general, efficient, rapid, and low-cost analysis method (Li J et al., 2020). Studies are beginning to combine several assays, however, it is unclear whether they can be used with large quantities of samples.

Visual inspection refers to the direct and rapid identification of microplastics by the naked eye or with the help of a microscope. Discrimination is based on the shape, size, color, and other physical characteristics of microplastics. Because the particle size of microplastics that can be observed by the eye is generally 1–5 mm, and there is the possibility of discoloration, wear, and other changes in the formation process of microplastics, the visual inspection method is unreliable. Eriksen M et al. (2013) reported that the misjudgment rate of microplastics by this method can reach 20%–70%, and the research results of Lenz R et al. (2015) showed that the success rate of identifying fibers by visual inspection (75%) is higher than that of pellets (64%).

Fourier transform infrared (FTIR) and Raman spectroscopy are commonly used for the detection of microplastics and are considered the most reliable methods for identifying the type and shape of microplastics. FTIR determines the type of microplastics in the sample by comparing the sample spectrum with the standard spectrum, has a stronger identification ability for polar groups (Lenz R et al., 2015), and can generally detect microplastics with particle size >20 μm. In addition, the reflection mode equipped with a focal plane array can overcome the large error of traditional instruments in the determination of non-uniform and uneven sample surfaces, which is an ideal method for identifying microplastics at present (Tang Q et al., 2019). However, it is uncertain whether the quantitative analysis of microplastics in environmental samples is reliable (Rocha-Santos T and Duarte AC, 2015). Raman spectroscopy is based on laser beams of different molecular and atomic structure characteristics of the different frequencies of backscattered light from the analysis of polymer types, which is higher than the resolution of FTIR, and the nonpolar groups of appraisal ability are stronger (Lenz R et al., 2015). When combined with microscopy, microplastic particles with particle size <1 μm can be identified and detected, and even local microscopic morphology can be observed (Tang QF et al., 2019). The common disadvantages of these two analytical methods are their high cost, long analytical time, and susceptibility to organic matter and impurities in the sample (Löder MGJ et al., 2017).

Thermal analysis can be used instead of spectroscopic methods to determine the content of microplastics in the samples. The most widely used methods are gas chromatography-mass spectrometry (Py/GC-MS) and thermogravimetric analysis (TGA), both of which require no pretreatment of samples. The disadvantage is that they can

**Table 10. Comparison of advantages and disadvantages of microplastics identification technology in soil.**

| Assays | Analytical methods | Advantage | Deficiency | References |
|---|---|---|---|---|
| Visual inspection | microscope | Direct and fast identification of microplastics | It ubjective and easy misjudge | Eriksen M et al., 2013<br>Lenz R et al., 2015 |
| Spectroscopy | FTIR | The microplastics are not damaged, and the identifaion results are moaccurate and reliable | Higher cost<br>septible to organictter and impurities in the sample | Tang QF et., 2019<br>Löder MGJ et al., 2017<br>Rocha-Santos T and Duarte A C, 2015 |
|  | Raman spectroscopy | The separation rate is higher and non-polar groups can be identified | Mcopastic content couldntbdtermined |  |
| Thermal analysis | Py/GC-MS<br>TGA | No sample pretreatment is required | They will generally damage the sample and should noteused if frhr analysis is reqed | Tang QF et al., 2019<br>Chen YL et al., 2022<br>Käppler A et al., 2018 |
| Emerging technologies | TED-GC-MS | It is quick and fast | Unknown | Erik D et al., 2017 |
|  | THz spectrometr | iferent spectral chcteristics of differenpllutants<br>High-restion imaging mode |  | Li YH et al., 2021<br>Mu SY et al., 2021 |

damage the sample and should not be used if other analyses are needed later (Käppler A et al., 2018). In addition, because they are closely related to temperature, they are not conducive to resolving complexes of similar quality and degradation temperature. Py/GC-MS is a technology used to determine the type of microplastics based on small-molecule compounds produced by the thermal cracking of microplastics. However, there is a possibility of misjudging microplastics with similar thermal cracking products (Tang QF et al., 2019). It is necessary to combine this method with other methods, such as visual inspection, to determine the morphology, color, and other characteristics of microplastics. TGA is also a method used to analyze microplastic categories through changes in microplastics after heating, and combined with differential scanning calorimetry (DSC) or mass spectrometry (MS), microplastic samples can be comprehensively and accurately analyzed. The combination of DSC and TGA can be used to identify PE and PP (Tang QF et al., 2019), and the combination of MS and TGA can be used to determine the PET in soil (David J et al., 2018).

In addition to these common techniques, two new approaches have received considerable attention. TED-GC-MS (a combination of TGA-solid-phase extraction and TDS-GC-MS) has been proven to be accurate and effective for the quantitative analysis of PE, PET, PP, and PS (Erik D et al., 2017). This method is quick and fast, which is valuable for further research. Although THz spectrometry technology has not been used for the detection of microplastics, it is a new technology that may be superior to other detection methods by taking advantage of the different spectral characteristics of different pollutants in soil and the high-resolution imaging mode (Li YH et al., 2021).

## 7. Conclusions

In this study, a large amount of literature on soil microplastics was collected, and the research progress on microplastic content characteristics, main sources, risks, and existing analytical techniques in the soil environment was reviewed. The following conclusions were drawn.

(1) Microplastics were detected in soils of different land types, mainly PP, PE, PS, PES, PVC and PET, and most of the sizes are less than 1 mm. The land use type and soil depth have a great influence on the content of microplastics in soil, and the content of microplastics in soil of industrial land and agricultural land is often higher than that of other land types, and the content decreases with increasing soil depth.

(2) The main source of microplastics in agricultural land is residual agricultural plastic film. The content of microplastics in soil is affected by the degradation ability of the film, mulching time of farmland, and recycling efficiency. In addition, sludge composting, rivers or sewage irrigation, and atmospheric deposition are common input routes for microplastics in soil. How to trace the source of soil microplastics is the next direction worth further research.

(3) On the one hand, microplastics enter the soil will change the physical and chemical properties, such as the soil porosity, pH, EC, etc. On the other hand, microplastics depends on the functional groups on its surface to interact with organic pollutants, antibiotics and heavy metals, and become the migration carrier of pollutants. Broken microplastics have a larger surface area and are more harmful to the soil.

(4) Microplastics in soil can interfere with the original order of microorganisms. They also can be absorbed by crops or eaten by soil animals. When microplastics enter into crops and animals, they can affect the normal development of crops and animals, and severely, lead to death. Soil microplastics will further threaten human health once they enter the food chain.

(5) At present, there is no industry standard for the extraction and detection of microplastics in soil, and most studies choose FTIR or thermal analysis technology, supplemented by visual inspection methods, when identifying microplastics. The existing detection methods have their own advantages and disadvantages, and it is necessary to further explore new identification technologies such as THz spectrometry.

## CRediT authorship contribution statement

Zong-fang Yang conceived of the presented idea. Yu-chen

Yan collected data and drafted the manuscript. All authors modified the manuscript and contributed to the final manuscript.

## Declaration of competing interest

The authors declare no conflicts of interest.

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## References

Abbasi S, Keshavarzi B, Moore F, Delshab H, Soltani N, Sorooshian A. 2017. Investigation of microrubbers, microplastics and heavy metals in street dust: a study in Bushehr City, Iran. Environmental Earth Sciences, 76(23), 1–19. doi: 10.1007/s12665-017-7137-0.

Abbasi S, Moore F, Keshavarzi B, Hopke PK, Naidu R, Rahman MM, Oleszczuk P, Karimi J. 2020. Pet-Microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. Science of the Total Environment, 744, 140984. doi: 10.1016/j.scitotenv.2020.140984.

An J, Liu HY, Zheng Y, Cheng J, Song C. 2021. Effects of soil microplastics residue on soybean seedlings growth and the physiological and biochemical characteristics. Journal of Sichuan Agricultural University, 39(01), 41–46 (in Chinese with English abstract). doi: 10.16036/j.issn.1000-2650.2021.01.007.

Auta HS, Emenike CU, Fauziah SH. 2017. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environment International, 102, 165–176. doi: 10.1016/j.envint.2017.02.013.

Awet TT, Kohl Y, Meier F, Straskraba S, Grun AL, Ruf T, Jost C, Drexel R, Tunc E, Emmerling C. 2018. Effects of polystyrene nanoparticles on the microbiota and functional diversity of enzymes in soil. Environmental Sciences Europe, 30(1), 11. doi: 10.1186/s12302-018-0140-6.

Baeza C, Cifuentes C, González P, Araneda A, Barra R. 2020. Experimental exposure of lumbricus terrestris to microplastics. Water, Air, and Soil Pollution, 231 (6). doi: 10.1007/s11270-020-04673-0

Cai LQ, Wang JD, Peng JP, Tan Z, Zhan ZW, Tan XL, Chen QQ. 2017. Characteristic of microplastics in the atmospheric fallout from Dongguan City, China: preliminary research and first evidence. Environmental Science and Pollution Research, 24(32), 24928–24935. doi: 10.1007/s11356-017-0116-x.

Cai LQ, Wang JD, Peng JP, Wu ZQ, Tan XL. 2018. Observation of the degradation of three types of plastic pellets exposed to UV irradiation in three different environments. Science of The Total Environment, 628–629, 740–747. doi: 10.1016/j.scitotenv.2018.02.079

Carr SA, Liu J, Tesoro AG. 2016. Transport and fate of microplastic particles in wastewater treatment plants. Water Research, 91, 174–182. doi: 10.1016/j.watres.2016.01.002.

Catarino AI, Thompson R, Sanderson W, Henry TB. 2017. Development and optimization of a standard method for extraction of microplastics in mussels by enzyme digestion of soft tissues. Environmental Toxicology and Chemistry, 36(4), 947–951. doi: 10.1002/etc.3608.

Chai BW, Yin H, Wei Q, Lü GN, Dang Z. 2021. Relationships between microplastic and surrounding soil in an e-waste zone of China. Environmental Science, 42(03), 1073–1080 (in Chinese with English abstract). doi: 10.13227/j.hjkx.202007245.

Chen YL, Sun K, Han LF, Gao B. 2022. Separation, identification, and quantification methods in soil microplastics analysis: a review. Acta Pedologica Sinica, 59(2), 364–380 (in Chinese with English abstract). doi: 10.11766/trxb202012070566.

Chen Y, Zhang Y, Su LH, Zhao X, Bu YQ, Li H, Zhang SH, Li J. 2020. Occurrence characteristics of microplastics in Nanjing urban wastewater treatment plant. China Environmental Science, 40(9), 3835–3841 (in Chinese with English abstract). doi: 10.19674/j.cnki.issn1000-6923.2020.0429.

Cole M, Webb H, Lindeque PK, Fileman ES, Halsband C, Galloway TS. 2015. Isolation of microplastics in biota-rich seawater samples and marine organisms. Scientific Reports, 4 (1). doi: 10.1038/srep04528

Corradini F, Meza P, Eguiluz R, Casado F, Huerta-Lwanga E, Geissen V. 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Science of the Total Environment, 671, 411–420. doi: 10.1016/j.scitotenv.2019.03.368.

Crichton EM, Noel M, Gies EA, Ross PS. 2017. A novel, density-independent and ftir-compatible approach for the rapid extraction of microplastics from aquatic sediments. Analytical Methods, 9(9), 1419–1428. doi: 10.1039/C6AY02733D.

Crossman J, Hurley RR, Futter M, Nizzetto L. 2020. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. Science of the Total Environment, 724, 138334. doi: 10.1016/j.scitotenv.2020.138334.

David J, Steinmetz Z, Kučerík J, Schaumann GE. 2018. Quantitative analysis of poly(ethylene terephthalate) microplastics in soil via thermogravimetry–mass spectrometry. Analytical Chemistry, 90(15), 8793–8799. doi: 10.1021/acs.analchem.8b00355.

de Souza Machado AA, Lau CW, Kloas W, Bergmann J, Bachelier JB, Faltin E, Becker R, Görlich AS, Rillig MC. 2019. Microplastics can change soil properties and affect plant performance. Environmental Science and Technology, 53(10), 6044–6052. doi: 10.1021/acs.est.9b01339.

Dehaut A, Cassone A, Frère L, Hermabessiere L, Himber C, Rinnert E, Rivière G, Lambert C, Soudant P, Huvet A, Duflos G, Paul-Pont I. 2016. Microplastics in seafood: benchmark protocol for their extraction and characterization. Environmental Pollution, 215, 223–233. doi: 10.1016/j.envpol.2016.05.018.

Ding F, Li SY, Lü XT, Dijkstra FA, Schaeffer S, An TT, Pei JB, Sun LJ, Wang JK. 2019. Opposite effects of nitrogen fertilization and plastic film mulching on crop N and P stoichiometry in a temperate agroecosystem. Journal of Plant Ecology, 12(4), 682–692. doi: 10.1093/jpe/rtz006.

Ding L, Mao RF, Guo XT, Yang XM, Zhang Q, Yang C. 2019. Microplastics in surface waters and sediments of the Wei River, in the Northwest of China. Science of the Total Environment, 667, 427–434. doi: 10.1016/j.scitotenv.2019.02.332.

Ding L, Zhang SY, Wang XY, Yang XM, Zhang CT, Qi YB, Guo XT. 2020. The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in North-Western China. Science of The Total Environment, 720, 137525. doi: 10.1016/j.scitotenv.2020.137525.

Dong MT, Luo ZJ, Xing XL, Zhang QQ, Sun Y. 2020. Separation of microplastics in soils and sediments with oil extraction protocol. Research of Environmental Sciences, 33(06), 1522–1529 (in Chinese with English abstract). doi: 10.13198/j.issn.1001-6929.2019.10.05.

Dris R, Gasperi J, Saad M, Mirande C, Tassin B. 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Marine Pollution Bulletin, 104(1–2), 290–293. doi: 10.1016/j.marpolbul.2016.01.006.

Eo S, Hong SH, Song YK, Han GM, Shim WJ. 2019. Spatiotemporal distribution and annual load of microplastics in the Nakdong River, South Korea. Water Research, 160, 228–237. doi: 10.1016/j.watres.2019.05.053.

Erik D, Paul E, Claus GB, Anne-Kathrin B, Rainer S, Ulrike B. 2017. Fast identification of microplastics in complex environmental samples by a thermal degradation method. Chemosphere, 174, 572–584. doi: 10.1016/j.chernosphere.2017.02.010.

Eriksen M, Mason S, Wilson S, Box C, Zellers A, Edwards W, Farley H, Amato S. 2013. Microplastic pollution in the surface waters of the Laurentian Great Lakes. Marine Pollution Bulletin, 77(1–2), 177–182. doi: 10.1016/j.marpolbul.2013.10.007.

Evangeliou N, Grythe H, Klimont Z, Heyes C, Eckhardt S, Lopez-Aparicio S, Stohl A. 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nature Communications, 11(1), 1–11. doi: 10.1038/s41467-020-17201-9.

Fei YF, Huang SY, Zhang HB, Tong YZ, Wen DS, Xia XY, Wang H, Luo YM, Barceló D. 2020. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. Science of the Total Environment, 707, 135634. doi: 10.1016/j.scitotenv.2019.135634.

Fuller S, Gautam A. 2016. A Procedure for measuring microplastics using pressurized fluid extraction. Environmental Science and Technology, 50(11), 5774–5780. doi: 10.1021/acs.est.6b00816.

Gao ML, Liu Y, Song ZG. 2019. Effects of polyethylene microplastic on the phytotoxicity of di-n-butyl phthalate in Lettuce (Lactuca Sativa L. Var. Ramosa Hort). Chemosphere, 237, 124482. doi: 10.1016/j.chemosphere.2019.124482.

Gatidou G, Arvaniti OS, Stasinakis AS. 2019. Review on the occurrence and fate of microplastics in sewage treatment plants. Journal of Hazardous Materials, 367, 504–512. doi: 10.1016/j.jhazmat.2018.12.081.

Gies EA, Lenoble JL, Noël M, Etemadifar A, Bishay F, Hall ER, Ross PS. 2018. Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada. Marine Pollution Bulletin, 133, 553–561. doi: 10.1016/j.marpolbul.2018.06.006.

Gong J, Xie P. 2020. Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics. Chemosphere, 254, 126790. doi: 10.1016/j.chemosphere.2020.126790.

He DF, Luo YM, Lu SB, Liu MT, Song Y, Lei LL. 2018. Microplastics in soils: analytical methods, pollution characteristics and ecological risks. TrAC Trends in Analytical Chemistry, 109, 163–172. doi: 10.1016/j.trac.2018.10.006.

Helcoski R, Yonkos LT, Sanchez A, Baldwin AH. 2020. Wetland soil microplastics are negatively related to vegetation cover and stem density. Environmental Pollution, 256, 113391. doi: 10.1016/j.envpol.2019.113391.

Huerta LE, Mendoza VJ, Ku QV, Chi JDLA, Sanchez DCL, Chi C, Escalona SG, Gertsen H, Salánki T, van der Ploeg M, Koelmans AA, Geissen V. 2017. Field evidence for transfer of plastic debris along a terrestrial food chain. Scientific Reports, 7(1), 14071. doi: 10.1038/s41598-017-14588-2.

Hüffer T, Metzelder F, Sigmund G, Slawek S, Schmidt TC, Hofmann T. 2019. Polyethylene microplastics influence the transport of organic contaminants in soil. Science of the Total Environment, 657, 242–247. doi: 10.1016/j.scitotenv.2018.12.047.

Hüffer T, Weniger AK, Hofmann T. 2018. Sorption of organic compounds by aged polystyrene microplastic particles. Environmental Pollution, 236, 218–225. doi: 10.1016/j.envpol.2018.01.022.

Hurley RR, Lusher AL, Olsen M, Nizzetto L. 2018. Validation of a method for extracting microplastics from complex, organic-rich, environmental matrices. Environmental Science and Technology, 52(13), 7409–7417. doi: 10.1021/acs.est.8b01517.

Jia QL, Chen H, Zhao X, Li L, Nie YH, Ye JF. 2019. Removal of Microplastics by Different Treatment Processes in Shanghai Large Municipal Wastewater Treatment Plants. Environmental Science, 40(09), 4105–4112 (in Chinese with English abstract). doi: 10.13227/j.hjkx.201903100.

Jiang CB, Yin LS, Li ZW, Wen XF, Luo X, Hu SP, Yang HY, Long YN, Deng B, Huang LZ, Liu YZ. 2019. Microplastic pollution in the rivers of the Tibet Plateau. Environmental Pollution, 249, 91–98. doi: 10.1016/j.envpol.2019.03.022.

Jiang XF, Chen H, Liao YC, Ye ZQ, Li M, Klobučar G. 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant vicia faba. Environmental Pollution, 250, 831–838. doi: 10.1016/j.envpol.2019.04.055.

Jiang Y, Yang F, Zhao Y, Wang J. 2020. Greenland sea gyre increases microplastic pollution in the surface waters of the Nordic Seas. Science of the Total Environment, 712, 136484. doi: 10.1016/j.scitotenv.2019.136484.

Jin T, Xue YH, Zhang MM, Zhou T, Liu HJ, Zhang K, Xi B. 2020. Research advances in regulations, standards and recovery of mulch film. Ecology and Environment Sciences, 29(02), 411–420 (in Chinese with English abstract). doi: 10.16258/j.cnki.1674-5906.2020.02.024.

Ju H, Zhu D, Qiao M. 2019. Effects of polyethylene microplastics on the gut microbial community, reproduction and avoidance behaviors of the soil springtail, Folsomia Candida. Environmental Pollution, 247, 890–897. doi: 10.1016/j.envpol.2019.01.097.

Käppler A, Fischer M, Scholz-Böttcher BM, Oberbeckmann S, Labrenz M, Fischer D, Eichhorn K, Voit B. 2018. Comparison of M-Atr-Ftir Spectroscopy and Py-Gcms as identification tools for microplastic particles and fibers isolated from river sediments. Analytical and Bioanalytical Chemistry, 410 (21). doi: 10.1007/s00216-018-1185-5

Kim J, Lee Y, Park J, Jung SM. 2022. Repeatable separation of microplastics integrating mineral oil extraction and a PDMS-Ni foam adsorbent in real soil. Chemical Engineering Journal, 429, 132517. doi: 10.1016/j.cej.2021.132517.

Kim SW, Kim D, Jeong S, An Y. 2020a. Size-dependent effects of polystyrene plastic particles on the nematode caenorhabditis elegans as related to soil physicochemical properties. Environmental Pollution, 258, 113740. doi: 10.1016/j.envpol.2019.113740.

Kim SW, Waldman WR, Kim T, Rillig MC. 2020b. Effects of different microplastics on nematodes in the soil environment: tracking the extractable additives using an ecotoxicological approach. Environmental Science & Technology, 54(21), 13868–13878. doi: 10.1021/acs.est.0c04641.

Kumar M, Xiong X, He M, Tsang DCW, Gupta J, Khan E, Harrad S, Hou D, Ok YS, Bolan NS. 2020. Microplastics as pollutants in agricultural soils. Environmental Pollutio, 265, 114980. doi: 10.1016/j.envpol.2020.114980.

Lares M, Ncibi MC, Sillanpää M, Sillanpää M. 2018. Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced mbr technology. Water Research, 133, 236–246. doi: 10.1016/j.watres.2018.01.049.

Lenz R, Enders K, Stedmon CA, Mackenzie DMA, Nielsen TG. 2015. A critical assessment of visual identification of marine microplastic using raman spectroscopy for analysis improvement. Marine Pollution Bulletin, 100(1), 82–91. doi: 10.1016/j.marpolbul.2015.09.026.

Leslie HA, van Velzen MJM, Brandsma SH, Vethaak AD, Garcia-Vallejo JJ, Lamoree MH. 2022. Discovery and quantification of plastic particle pollution in human blood. Environment International, 163, 107199. doi: 10.1016/j.envint.2022.107199.

Li J, Guo K, Cao YS, Wang SS, Song Y, Zhang HB. 2021. Enhance in mobility of oxytetracycline in a sandy loamy soil caused by the presence of microplastics. Environmental Pollution, 269, 116151. doi: 10.1016/j.envpol.2020.116151.

Li J, Song Y, Cai YB. 2020. Focus topics on microplastics in soil: analytical methods, occurrence, transport, and ecological risks. Environmental Pollution, 257, 113570. doi: 10.1016/j.envpol.2019.113570.

Li LZ, Luo YM, Peijnenburg WJGM, Li RJ, Yang J, Zhou Q. 2020. Confocal measurement of microplastics uptake by plants. MethodsX, 7, 100750. doi: 10.1016/j.mex.2019.11.023.

Li PF, Hou DY, Wang LW, Wu WM, Pan SZ. 2021. (Micro) plastics pollution in agricultural soils: sources, transportation, ecological effects and preventive strategies. Acta Pedologica Sinica, 58(02), 314–330 (in Chinese with English abstract). doi: 10.11766/trxb202009190526.

Li QL, Wu JT, Zhao XP, Gu XY, Ji R. 2019. Separation and identification of microplastics from soil and sewage sludge. Environmental Pollution, 254, 113076. doi: 10.1016/j.envpol.2019.113076.

Li XW, Chen LB, Mei QQ, Dong B, Dai XH, Ding GJ, Zeng EY. 2018. Microplastics in sewage sludge from the wastewater treatment plants in China. Water Research, 142, 75–85. doi: 10.1016/j.watres.2018.05.034.

Li XW, Ji YY, Mei QQ, Chen LB, Zhang XL, Dong B, Dai XH. 2019. Review of microplastics in wastewater and sludge of wastewater treatment plant. Water Purification Technology, 38(07), 13–22 (in Chinese with English abstract). doi: 10.15890/j.cnki.jsjs.2019.07.003.

Li YW, Shao LY, Wang WH, Zhang MY, Feng XL, Li WJ, Zhang DZ. 2020. Airborne fiber particles: types, size and concentration observed in Beijing. Science of the Total Environment, 705, 135967. doi: 10.1016/j.scitotenv.2019.135967.

Li YH, Yao JJ, Nie PC, Feng XP, Liu JZ. 2021. An effective method for the rapid detection of microplastics in soil. Chemosphere, 276, 128696. doi: 10.1016/j.chemosphere.2020.128696.

Lian JP, Wu JN, Xiong HX, Zeb A, Yang TZ, Su XM, Su LJ, Liu WT. 2020. Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (Triticum aestivum L). Journal of Hazardous Materials, 385, 121620. doi: 10.1016/j.jhazmat.2019.121620.

Lian YH, Liu WT, Shi RY, Zeb A, Wang Q, Li JT, Zheng ZQ, Tang JC. 2022. Effects of polyethylene and polylactic acid microplastics on plant growth and bacterial community in the soil. Journal of Hazardous Materials, 435, 129057. doi: 10.1016/j.jhazmat.2022.129057.

Liao YC, Nazygul J, Li M, Wang XL, Jiang LJ. 2019. Effects of microplastics on the growth, physiology, and biochemical characteristics of wheat (triticum aestivum). Environmental Science, 40(10), 4661–4667 (in Chinese with English abstract). doi: 10.13227/j.hjkx.201903113.

Liu HF, Yang XM, Liu GB, Liang CT, Xue S, Chen H, Ritsema CJ, Geissen V. 2017. Response of soil dissolved organic matter to microplastic addition in Chinese Loess soil. Chemosphere, 185, 907–917. doi: 10.1016/j.chemosphere.2017.07.064.

Liu J, Ma Y, Zhu DQ, Xia TJ, Qi Y, Yao Y, Guo XR, Ji R, Chen W. 2018. Polystyrene nanoplastics-enhanced contaminant transport: role of irreversible adsorption in glassy polymeric domain. Environmental Science and Technology, 52(5), 2677–2685. doi: 10.1021/acs.est.7b05211.

Liu JB, Qin JJ, Zhu L, Zhu KC, Liu Z, Jia HZ, Lichtfouse E. 2022. The protective layer formed by soil particles on plastics decreases the toxicity of polystyrene microplastics to earthworms (Eisenia Fetida). Environment International, 162, 107158. doi: 10.1016/j.envint.2022.107158.

Liu K, Wang XH, Fang T, Xu P, Zhu LX, Li DJ. 2019. Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Science of the Total Environment, 675, 462–471. doi: 10.1016/j.scitotenv.2019.04.110.

Liu MT, Lu SB, Song Y, Lei L, Hu JN, Lü WW, Zhou WZ, Cao CJ, Shi HH, Yang XF, He DF. 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. Environmental Pollution, 242, 855–862. doi: 10.1016/j.envpol.2018.07.051.

Liu RP, Li ZZ, Liu F, Dong Y, Jiao JG, Sun PP, M El-Wardany R. 2021a. Microplastic pollution in Yellow River, China: current status and research progress of biotoxicological effects. China Geology, 4(04), 585–592. doi: 10.31035/cg2021081.

Liu RP, Dong Y, Quan GC, Zhu H, Xu YN, M Elwardany R. 2021b. Microplastic pollution in surface water and sediments of Qinghai-Tibet Plateau: current status and causes. China Geology, 4(1), 178–184. doi: 10.31035/cg2021011.

Liu YC, Wu L, Shi GW, Cao SW, Li YS. 2022. Characteristics and sources of microplastic pollution in the water and sediments of the Jinjiang River Basin, Fujian Province, China. China Geology, 5, 429–438. doi: 10.31035/cg2022051.

Löder MG J, Imhof HK, Ladehoff M, Löschel LA, Lorenz C, Mintenig S, Piehl S, Primpke S, Schrank I, Laforsch C, Gerdts G. 2017. Enzymatic purification of microplastics in environmental samples. Environmental Science and Technology, 51(24), 14283–14292. doi: 10.1021/acs.est.7b03055.

Long ZX, Pan Z, Wang WL, Ren JY, Yu XG, Lin LY, Lin H, Chen HZ, Jin XL. 2019. Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China. Water Research, 155, 255–265. doi: 10.1016/j.watres.2019.02.028.

Luo YY, Zhang YY, Xu YB, Guo XT, Zhu LY. 2020. Distribution characteristics and mechanism of microplastics mediated by soil physicochemical properties. Science of the Total Environment, 726, 138389. doi: 10.1016/j.scitotenv.2020.138389.

Maliwan T, Pungrasmi W, Lohwacharin J. 2021. Effects of microplastic accumulation on floc characteristics and fouling behavior in a membrane bioreactor. Journal of Hazardous Materials, 411, 124991. doi: 10.1016/j.jhazmat.2020.124991.

Mason SA, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, Fink P, Papazissimos D, Rogers DL. 2016. Microplastic pollution is widely detected in us municipal wastewater treatment plant effluent. Environmental Pollution, 218, 1045–1054. doi: 10.1016/j.envpol.2016.08.056.

Mei WP, Chen GE, Bao JQ, Song MK, Li YT, Luo CL. 2020. Interactions between microplastics and organic compounds in aquatic environments: A mini review. The Science of the total environment, 736, 139472. doi: 10.1016/j.scitotenv.2020.139472.

Melanie B, Sophia M, Sebastian P, Mine BT, Jürg T, Gunnar G. 2019. White and wonderful? microplastics prevail in snow from the alps to the arctic Science Advances, 5(8), 1157. doi: 10.1126/sciadv.aax1157.

Mu SY, Yang MH, Chen QQ, Huang HC, Ma YY, Hao SB, Zhang ZL, Zheng ZY. 2021. Study on detection and analysis of soil pollutants by terahertz spectroscopy. Experimental Technology and Management, 38(4), 89–93. doi: 10.16791/j.cnki.sjg.2021.04.019.

Murphy F, Ewins C, Carbonnier F, Quinn B. 2016. Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environmental Science and Technology, 50(11), 5800–5808. doi: 10.1021/acs.est.5b05416.

Nizzetto L, Futter M, Langaas S. 2016. Are agricultural soils dumps for microplastics of urban origin? Environmental Science and Technology, 50(20), 10777–10779. doi: 10.1021/acs.est.6b04l40.

Nuelle M, Dekiff J H, Remy D, Fries E. 2014. A new analytical approach for monitoring microplastics in marine sediments. Environmental Pollution, 184, 161–169. doi: 10.1016/j.envpol.2013.07.027.

Okoffo ED, O'Brien S, Ribeiro F, Burrows SD, Toapanta T, Rauert C, O'Brien JW, Tscharke BJ, Wang X, Thomas KV. 2021. Plastic particles in soil: state of the knowledge on sources, occurrence and distribution, analytical methods and ecological impacts. Environmental Science-processes and Impacts, 23(2), 240–274. doi:

10.1039/d0em00312c.

Oluchi M, Graham J, Chris P, Prasad K. 2020. A new contaminant superhighway? a review of sources, measurement techniques and fate of atmospheric microplastics. Water, Air, and Soil Pollution: An International Journal of Environmental Pollution, 231 (2), 1–27. doi: 10.1007/s11270-020-4459-4.

Piehl S, Leibner A, Löder MGJ, Dris R, Bogner C, Laforsch C. 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. Scientific Reports, 8(1), 17950. doi: 10.1038/s41598-018-36172-y.

Prata JC. 2018. Airborne microplastics: consequences to human health? Environmental Pollution, 234, 115–126. doi: 10.1016/j.envpol.2017.11.043.

Prata JC, Da Costa JP, Duarte AC, Rocha-Santos T. 2019. Methods for sampling and detection of microplastics in water and sediment: a critical review. TrAC Trends in Analytical Chemistry, 110, 150–159. doi: 10.1016/j.trac.2018.10.029.

Prendergast-Miller MT, Katsiamides A, Abbass M, Sturzenbaum SR, Thorpe KL, Hodson ME. 2019. Polyester-derived microfibre impacts on the soil-dwelling earthworm Lumbricus Terrestris. Environmental Pollution, 251, 453–459. doi: 10.1016/j.envpol.2019.05.037.

Qi YL, Yang XM, Pelaez AM, Huerta Lwanga E, Beriot N, Gertsen H, Garbeva P, Geissen V. 2018. Macro- and micro- plastics in soil-plant system: effects of plastic mulch film residues on wheat (Triticum Aestivum) growth. Science of the Total Environment, 645, 1048–1056. doi: 10.1016/j.scitotenv.2018.07.229.

Qian HF, Zhang M, Liu GF, Lu T, Qu Q, Du BB, Pan XL. 2018. Effects of soil residual plastic film on soil microbial community structure and fertility. Water, Air, and Soil Pollution, 229 (8), 1. doi: 10.1007/s11270-018-3916-9.

Rachid D, Johnny G, Cécile M, Corinne M, Mohamed G, Valérie L, Bruno T. 2017. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environmental Pollution, 221(16), 453–458. doi: 10.1016/j.envpol.2016.12.013.

Richard H, Carpenter EJ, Komada T, Palmer PT, Rochman CM. 2019. Biofilm facilitates metal accumulation onto microplastics in estuarine waters. Science of the Total Environment, 683, 600–608. doi: 10.1016/j.scitotenv.2019.04.331.

Rillig MC. 2012. Microplastic in terrestrial ecosystems and the soil? Environmental Science and Technology, 46 (12), 6453–6454. doi: 10.1021/es302011r.

Rillig MC, Bonkowski M. 2018. Microplastic and soil protists: a call for research. Environmental Pollution, 241, 1128–1131. doi: 10.1016/j.envpol.2018.04.147.

Rocha-Santos T, Duarte AC. 2015. A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment. TrAC Trends in Analytical Chemistry, 65, 47–53. doi: 10.1016/j.trac.2014.10.011.

Roland G, Jenna RJ, Kara LL. 2017. Production, use, and fate of all plastics ever made. Science Advances, 3(7), 1700782. doi: 10.1126/sciadv.1700782.

Salvador CF, Turra A, Baruque-Ramos J. 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Science of the Total Environment, 598, 1116–1129. doi: 10.1016/j.scitotenv.2017.04.172.

Scheurer M, Bigalke M. 2018. Microplastics in Swiss floodplain soils. Environmental Science and Technology, 52(6), 3591–3598. doi: 10.1021/acs.est.7b06003.

Schwabl P, Koppel S, Konigshofer P, Bucsics T, Trauner M, Reiberger T, Liebmann B. 2019. Detection of various microplastics in human stool: a prospective case series. Annals of Internal Medicine, 171(7), 453–457. doi: 10.7326/M19-0618.

Song DX, Ma L, Wang QJ. 2021. Occurrence characteristics and environmental effects of microplastics in typical farmland soils in Baoji area. Journal of Arid Land Resources and Environment, 35(02), 170–175 (in Chinese with English abstract). doi: 10.13448/j.cnki.jalre.2021.056.

Song H, Luo XM, Zhang L, He BN, Li JW, Wang YP. 2019. Characteristic analysis of methyl orange adsorption on microplastics in water. Earth Science Frontiers, 26(6), 19–27. doi: 10.13745/j.esf.sf.2019.7.1.

Song Y, Cao CJ, Qiu R, Hu JN, Liu MT, Lu SB, Shi HH, Raley-Susman KM, He DF. 2019. Uptake and adverse effects of polyethylene terephthalate microplastics fibers on terrestrial snails (Achatina Fulica) after soil exposure. Environmental Pollution, 250, 447–455. doi: 10.1016/j.envpol.2019.04.066.

Steve A, Deonie A, Vernon RP, Gaël L R, Pilar DJ, Anaëlle S, Stéphane B, Didier G. 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nature Geoscience, 12(5), 339–344. doi: 10.1038/s41561-019-0335-5.

Tang GL, Hu B, Kang ZL, Meng CC, Zhang XY, Zhang LQ, Feng HY, Sun WP. 2013. Current status and problems on waste plastic recycling. Recyclable Resources and Circular Economy, 6(01), 31–35 (in Chinese with English abstract). doi: 10.3969/j.issn.1674-0912.2013.01.012.

Tang QF, Li QM, Wei XX, Shao P, Gao LJ, Chen QR, Hu GH, Liu WL, Gao X. 2019. Progress on research of analysis techniques for microplastics in environmental samples. Journal of Instrumental Analysis, 38(08), 1009–1019 (in Chinese with English abstract). doi: 10.3969/j.issn.1004-4957.2019.08.019.

Thomas M, Stefan F, Andreas K, Patricia B. 2019. Using castor oil to separate microplastics from four different environmental matrices. Analytical Methods, 11(13), 1788–1794. doi: 10.1039/c8ay02559b.

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AW, Mcgonigle D, Russell AE. 2004. Lost at sea: where is all the plastic? Science, 304 (5672), 838. doi: 10.1126/science.1094559.

Tribedi P, Dey S. 2017. Pre-oxidation of low-density polyethylene (LDPE) by ultraviolet light (UV) promotes enhanced degradation of ldpe in soil. Environmental Monitoring and Assessment, 189(12), 624. doi: 10.1007/s10661-017-6351-2.

Van Cauwenberghe L, Devriese L, Galgani F, Robbens J, Janssen CR. 2015. Microplastics in sediments: a review of techniques, occurrence and effects. Marine Environmental Research, 111, 5–17. doi: 10.1016/j.marenvres.2015.06.007.

van den Berg P, Huerta-Lwanga E, Corradini F, Geissen V. 2020. Sewage sludge application as a vehicle for microplastics in eastern Spanish agricultural soils. Environmental Pollution, 261, 114198. doi: 10.1016/j.envpol.2020.114198.

Wang FT, Bao K, Huang CS, Liu RP, Han WJ, Yi CY, Li L, Zhou Y. 2022. Distribution, characteristics, and research status of microplastics in the trunk stream and main lakes of the Yangtze River: A review. China Geology, 5(1), 171–184. doi: 10.31035/cg2022002.

Wan HY, Wang JK, Zhang W. 2022. Key influencing factors for interactions between microplastics and heavy metals, persistent organic pollutants, and antibiotics in soil. Journal of Agricultural Resources and Environment, 39(4), 643–650 (in Chinese with English abstract). doi: 10.13254/j.jare.2021.0123.

Wan Y, Wu CX, Xue Q, Hui XMN. 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Science of the Total Environment, 654, 576–582. doi: 10.1016/j.scitotenv.2018.11.123.

Wang FY, Zhang XQ, Zhang SQ, Zhang SW, Sun YH. 2020a. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere, 254, 126791. doi: 10.1016/j.chemosphere.2020.126791.

Wang FY, Zhang XQ, Zhang SQ, Zhang SW, Adams CA, Sun YH. 2020b. Effects of co-contamination of microplastics and Cd on plant growth and Cd accumulation. Toxics, 8(2), 36. doi: 10.3390/toxics8020036.

Wang J, Coffin S, Sun CL, Schlenk D, Gan J. 2019. Negligible effects of microplastics on animal fitness and hoc bioaccumulation in earthworm eisenia fetida in soil. Environmental Pollution, 249, 776–784. doi: 10.1016/j.envpol.2019.03.102.

Wang QJ, Zhang Y, Wangjin XX, Wang YL, Meng GH, Chen YH. 2020. The adsorption behavior of metals in aqueous solution by microplastics effected by uv radiation. Journal of Environmental Sciences, 87, 272–280. doi: 10.1016/j.jes.2019.07.006.

Wang XH, Li CJ, Liu K, Zhu LX, Song ZY, Li DJ. 2020. Atmospheric microplastic over the South China Sea and East Indian Ocean: abundance, distribution and source. Journal of Hazardous Materials, 389, 121846. doi: 10.1016/j.jhazmat.2019.121846.

Wang ZC, Meng Q, Yu LY, Yang WH, Li WP, Yang JL, Yang F. 2020a. Occurrence characteristics of microplastics in farmland soil of Hetao Irrigation District, Inner Mongolia. Transactions of the Chinese Society of Agricultural Engineering, 36(03), 204–209 (in Chinese with English abstract). doi: 10.11975/j.issn.1002-6819.2020.03.025.

Wang ZC, Meng Q, Li WP, Yu LH, Qin YM, Hao WT. 2020b. Effect of different digestion methods on microplastic quality and surface characteristics. Chinese Journal of Environmental Engineering, 14(05), 1385–1393. doi: 10.12030/j.cjee.201907166.

Xiong W, Mei X, Mi BB, Yang H, Han ZZ, Zhang Y, Lü WC. 2022. Current status and cause analysis of microplastic pollution in sea areas in China. China Geology, 5(01), 160–170. doi: 10.31035/cg2021072.

Xu P, Peng GY, Zhu LX, Bai MY, Li DJ. 2019. Spatial-temporal distribution and pollution load of microplastics in the Changjiang Estuary. China Environmental Science, 39(05), 2071–2077 (in Chinese with English abstract). doi: 10.19674/j.cnki.issn1000-6923.2019.0248.

Xu, ZL, Qian XT, Wang C, Zhang CR, Tang T, Zhao XP, Li LY. 2020. Environmentally relevant concentrations of microplastic exhibits negligible impacts on thiacloprid dissipation and enzyme activity in soil. Environmental Research, 189, 109892. doi: 10.1016/j.envres.2020.109892.

Yan YY, Chen ZH, Zhu FX, Zhu CY, Wang C, Gu C. 2020. Correction to: effect of polyvinyl chloride microplastics on bacterial community and nutrient status in two agricultural soils. Bulletin of Environmental Contamination and Toxicology, 106(2), 236. doi: 10.1007/s00128-020-02963-1.

Yang J, Cang L, Qiu W, Yang JL, Zhou DM. 2019. Effects of different soil environmental factors on tetracycline adsorption of microplastics. Journal of Agro-Environment Science, 38(11), 2503–2510 (in Chinese with English abstract). doi: 10.11654/jaes.2019-0490.

Yonkos LT, Friedel EA, Perez-Reyes AC, Ghosal S, Arthur CD. 2014. Microplastics in four estuarine rivers in the Chesapeake Bay, U. S. A. Environmental Science and Technology, 48(24), 14195–14202. doi: 10.1021/es5036317.

Yu GB, Chen MZ, Tao P. 2017. Study on the removal of organic matter for separation and analysis of microplastics in sugarcane soil. Sugarcane and Canesugar, (02), 66–70 (in Chinese with English abstract). doi: 10.3969/j.issn.1005-9695.2017.02.012.

Zhang F, Zhang WJ, Qi JG, Li FM. 2018. A regional evaluation of plastic film mulching for improving crop yields on the Loess Plateau of China. Agricultural and Forest Meteorology, 248, 458–468. doi: 10.1016/j.agrformet.2017.10.030.

Zhang GS, Liu YF. 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Science of the Total Environment, 642, 12–20. doi: 10.1016/j.scitotenv.2018.06.004.

Zhang HB, Wang JQ, Zhou BY, Zhou Y, Dai ZF, Zhou Q, Chriestie P, Luo YM. 2018. Enhanced adsorption of oxytetracycline to weathered microplastic polystyrene: kinetics, isotherms and influencing factors. Environmental Pollution, 243, 1550–1557. doi: 10.1016/j.envpol.2018.09.122.

Zhang LS, Xie YS, Liu JY, Zhong S, Qian YJ, Gao P. 2020. An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. Environmental Science and Technology, 54(7), 4248–4255. doi: 10.1021/acs.est.9b07905.

Zhang QJ, Liu T, Liu L, Fan YF, Rao WX, Zheng JL, Qian X. 2021. Distribution and sedimentation of microplastics in Taihu Lake. Science of the Total Environment, 795, 148745. doi: 10.1016/j.scitotenv.2021.148745.

Zhang SL, Wang JQ, Liu X, Qu FJ, Wang XS, Wang XR, Li Y, Sun YK. 2019. Microplastics in the environment: A review of analytical methods, distribution, and biological effects. TrAC - Trends in Analytical Chemistry, 111, 62–72. doi: 10.1016/j.trac.2018.12.002.

Zhao SY, Zhu LX, Wang T, Li DJ. 2014. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Marine Pollution Bulletin, 86(1-2), 562–568. doi: 10.1016/j.marpolbul.2014.06.032.

Zhou BY, Wang JQ, Zhang HB, Shi HH, Fei YF, Huang SY, Tong YZ, Wen DS, Luo YM, Barceló D. 2020. Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, East China: multiple sources other than plastic mulching film. Journal of Hazardous Materials, 388, 121814. doi: 10.1016/j.jhazmat.2019.121814.

Zhou Q, Tian CG, Luo YM. 2017. Various forms and deposition fluxes of microplastics identified in the coastal urban atmosphere. Chinese Science Bulletin, 62(33), 3902–3909. doi: 10.1360/n972017-00956.

Zhou Q, Zhang HB, Fu CC, Zhou Y, Dai ZF, Li Y, Tu C, Luo YM. 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma, 322, 201–208. doi: 10.1016/j.geoderma.2018.02.015.

Zhou YF, Liu XN, Wang J. 2019. Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. Science of the Total Environment, 694, 133798. doi: 10.1016/j.scitotenv.2019.133798.

Zhu FX, Zhu CY, Wang C, Gu C. 2019. Occurrence and ecological impacts of microplastics in soil systems: a review. Bulletin of Environmental Contamination and Toxicology, 102(6), 741–749. doi: 10.1007/s00128-019-02623-z.

Zhu YE, Wen HX, Li THX, Li H, Wu C, Zhang GX, Yan J. 2021. Distribution and Sources of Microplastics in Farmland Soil Along the Fenhe River. Environmental Science, 42(08), 3894–3903 (in Chinese with English abstract). doi: 10.13227/j.hjkx.202012072.

Ziajahromi S, Neale PA, Rintoul L, Leusch FDL. 2017. Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water Research, 112, 93–99. doi: 10.1016/j.watres.2017.01.042.

Zou JY, Liu XP, Zhang DM, Yuan X. 2020. Adsorption of three bivalent metals by four chemical distinct microplastics. Chemosphere, 248. doi:10.1016/j.chemosphere.2020.126064