Prioritizing Soil Microplastic Pollution Research to Mitigate Ecological and Food Chain Risks: Postprint

Authors: Luo Yongming, Zhou Qian, Zhang Haibo, Pan Xiangliang, Tu Chen, Li Lianzhen, Yang Jie

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Abstract

Marine microplastic pollution has attracted global attention as an emerging environmental issue. In contrast, microplastic pollution in soils, particularly agricultural soils, has not yet garnered widespread concern. This article reviews research progress on the sources, accumulation, degradation, and migration of microplastics in soils, as well as their potential risks to ecological environments and food chains, and proposes recommendations for strengthening research and regulatory measures. The article notes that the fragmentation of agricultural plastic film, application of organic fertilizers, wastewater irrigation, agricultural utilization of sewage sludge, atmospheric deposition, and surface runoff have become sources of microplastics in soils, potentially leading to microplastic accumulation in soil-food crop systems and affecting soil biota behavior. The article argues that research and understanding remain lacking regarding the occurrence, migration, degradation, and environmental risks of microplastics entering soils, their accumulation in plants and animals and associated bioecological and food chain risks, and consequently risks to human health; discussion and awareness are also lacking on how to strengthen prevention, control, and remediation of soil microplastic pollution. Therefore, the article calls for increased attention to research on soil microplastic pollution to prevent ecological and food chain risks; and recommends that China should accelerate the establishment of analytical methods for soil microplastics, promptly initiate research on microplastic pollution and remediation in soil environments, investigate the accumulation, release, transformation, and ecological effects of microplastics, additives, and their degradation products in soil environments, assess the risks of microplastics and their co-contaminants to soil ecosystems, food chains, and human health, establish a source control and remediation technology system for soil microplastic pollution, and provide scientific basis and technical support for

the supervision and governance of microplastic pollution in soils and terrestrial ecosystems.

Full Text

Pay Attention to Research on Microplastic Pollution in Soil for Prevention of Ecological and Food Chain Risks

LUO Yongming[1,2,5*], **ZHOU Qian**[2,5], **ZHANG Haibo**[1,3], **PAN Xiangliang**[4], **TU Chen**[2], **LI Lianzhen**[2,5], **YANG Jie**[1,5]

[1]CAS Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China
[2]CAS Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China
[3]Zhejiang Key Laboratory of Soil Contamination Bioremediation, School of Environmental and Resource Sciences, Zhejiang Agricultural and Forest University, Hangzhou 311300, China
[4]College of Environment, Zhejiang University of Technology, Hangzhou 310014, China
[5]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Marine microplastic pollution, considered an emerging environmental problem, has gained global recognition. Comparatively, microplastic pollution in soil, particularly in agricultural land, has not received widespread attention. This paper reviews research progress on the sources, accumulation, degradation, migration, and potential risks to the ecological environment and food chain of microplastics in soil, and proposes recommendations for strengthening research and regulatory countermeasures. The article points out that the fragmentation of agricultural plastic film, application of organic fertilizer, wastewater irrigation, sewage sludge utilization, atmospheric deposition, and surface runoff have become sources of microplastics in soil, potentially leading to accumulation in soil-edible crop systems and affecting soil organism behavior.

The article argues that research and understanding are still lacking regarding the forms, migration, degradation, and environmental risks of microplastics entering soil, as well as their accumulation in animals and plants and associated ecological and food chain risks, and consequently their risks to human health. Discussion and awareness of how to strengthen prevention, control, and remediation of soil microplastic pollution are also lacking. Therefore, the article proposes that attention should be paid to research on microplastic pollution in soil to prevent ecological and food chain risks. It is recommended that China should accelerate the establishment of analytical methods for soil microplastics, promptly deploy research on environmental microplastic pollution and remediation in soil, investigate the accumulation, release, transformation, and ecological environmental effects of microplastics, additive substances, and their degradation products in soil environments, assess the risks of microplastics and their associated pollutants to soil ecosystems, food chains, and human health, and establish a technical system for source control and remediation of soil microplastic pollution, thereby providing scientific basis and technical support for the supervision and remediation of microplastic pollution in soil and terrestrial ecosystems.

Keywords: microplastics, soil, environmental behavior, combined pollution, ecological and food chain risks, governance and remediation

Microplastics refer to plastic pollutants in the environment with particle sizes less than 5 mm, including fragments, fibers, particles, foams, films, and other morphological types. Microplastic pollution has become a global environmental issue, with particular attention paid to the sources, abundance, environmental behavior, and ecological effects of microplastics in marine and coastal environments [1-4]. Recent studies indicate that microplastic pollution in terrestrial environments, especially in soil, should also receive sufficient attention [5]. Some researchers have pointed out that the abundance of microplastics in terrestrial environments may be 4-23 times that in the ocean, with annual input of microplastics into agricultural soils far exceeding input into global oceans [6].

To date, limited survey data have shown that soil contains considerably high levels of microplastic pollution. For example, Fuller and Gautam [7] found microplastic content reaching 0.03%-6.7% in a survey of industrial area soils in Sydney, Australia. Some researchers even believe that microplastic content in soils at certain plastic pollution hotspots may be as high as 60% [8,9]. Investigations in Swiss floodplains also found microplastic pollution in 90% of soil samples, with pollution levels correlating with population density in the watershed, demonstrating the contribution of human activities to soil microplastic pollution [10]. China is reported to be a major emitter of plastic waste, with coastal areas alone estimated to discharge 1.32-3.53 million tons of plastic waste annually, ranking first globally [1]. Although domestic investigations have been conducted on the types, abundance, and distribution of microplastics in coastal tidal flat soils [6,11], only two reports exist on microplastic pollution in farmland soils [12,13]. Therefore, there is an urgent need to strengthen research on the sources, distribution, and ecological and food chain risks of microplastics in agricultural soils to provide scientific basis for risk control and remediation of farmland soil microplastic pollution in China.

Sources of Microplastics in Soil

Sewage Sludge Application Introduces Microplastics International investigations of microplastics in wastewater treatment plants have found that approximately 90% of microplastics accumulate in sludge after sewage treatment [14]. Surveys of urban sludge in the United States, Germany, Finland, and Sweden have also shown that microplastic content in sludge ranges from 1,500-24,000 particles/kg [15-17]. Li et al. [18] investigated 79 sludge samples from 28 wastewater treatment plants across 11 provinces in China, finding microplastic content ranging from 1,600-56,400 particles/kg, with an average of 22,700$±$12,100 particles/kg, similar to international findings. Conventional sludge pretreatment methods (such as lime stabilization, anaerobic digestion, and thermal drying) are ineffective at removing microplastics [16]. Therefore, applying these sludges as fertilizer leads to microplastic accumulation in soil. Based on estimates from sludge application in North America and Europe, annual microplastic input into soil through sludge application is 63,000-430,000 tons in North America and 44,000-300,000 tons in Europe [6]. This data is already far higher than the annual input of 93,000-236,000 tons of microplastics into global oceans. China’ s annual sludge production is approximately 30-40 million tons, with agricultural utilization rate of less than 10% [19] but still increasing annually [20]. Clearly, land application of sewage sludge is an important source of microplastics in agricultural soils. Previous research has extensively studied the accumulation and hazards of heavy metals, persistent organic pollutants, antibiotics, pathogens, and parasite eggs in soil-plant systems during sludge application [21-23], but microplastic soil pollution remains understudied.

Long-term Organic Fertilizer Application Leads to Microplastic Accumulation Organic fertilizer has become an indispensable input in agricultural production, with even greater application rates in facility agriculture. Compared to sludge, data on microplastics in organic fertilizer and their input into soil through agricultural application are even more scarce. Currently, only three reports exist on plastic pollution in organic fertilizer. Bläsing and Amelung [24] compared three organic fertilizer samples from a processing plant in Bonn, Germany, finding visually identifiable plastic fragments (>0.5 mm) at 2.38-180 mg/kg. A survey in Slovenia found even higher plastic content in organic fertilizer, reaching 1,200 mg/kg [25]. Weithmann et al. [26] observed 14-895 particles/kg for sizes >1 mm. These three reports all focus on plastic fragments >0.5 mm in organic fertilizer, with the pollution status of smaller particle sizes still unknown. It can be anticipated that microplastics <0.5 mm, particularly micro- and nano-scale plastics, will be present at even higher abundances. China is a major producer and user of organic fertilizer, with annual production of commercial organic fertilizer exceeding 25 million tons and actual application of approximately 22 million tons [27]. Based on current survey data of microplastics in organic fertilizer, estimated annual microplastic input into Chinese farmland soils is 52.4-26,400 tons. Considering the content of microplastics <0.5 mm and the annual increase in organic fertilizer production and application, the actual amount will be even higher. Thus, organic fertilizer application is another important pathway for microplastic accumulation in farmland soils.

Agricultural Plastic Film Residue Decomposition Forms Microplastic Pollution China’ s agricultural plastic film usage reached 2.6036 million tons in 2015, including 1.455 million tons of mulch film, accounting for approximately 90% of global mulch film usage. Mulch film coverage exceeded 18.33 million hectares, but recovery rates were less than 60% [28]. The main component of agricultural mulch film is polyethylene (PE), including high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). Polyvinyl chloride (PVC) film has been banned in the United States due to its high toxicity [29]. Overall, the thickness of agricultural mulch film used in China is much thinner than that required in developed countries such as Europe and Japan, with some regions using film thinner than 0.005 mm, while developed countries typically require thickness above 0.02 mm. Thin film is difficult to recover and prone to aging and fragmentation. Residual film in soil more easily forms microplastic pollution while also releasing plasticizer pollutants such as phthalates [30]. Residual film can decompose to form plastic fragments and even microplastics [29,31]. Therefore, mulch film residue decomposition is another important source of microplastics in agricultural soils.

Atmospheric Microplastic Deposition Enters Surface Soil In addition to microplastics from sludge, organic fertilizer, and film residues, soil can also receive microplastics through atmospheric deposition. Zhou et al. [32] first reported the types, deposition flux, and seasonal variation characteristics of microplastics in the atmospheric environment of Chinese coastal cities, with atmospheric microplastic deposition flux reaching 1.46$×10^{5}$ particles/(m^2 · a) and fiber types reaching 1.38$×10^{5}$ particles/(m^2 · a). Variation in deposition flux for different microplastic types ranged from 0-6.02$×10^{2}$ particles/(m^2 · d), with fiber types being the highest. Dris et al. [33] also investigated atmospheric microplastics in the 2,500 km^2 Paris metropolitan area, finding that fiber types dominated, with approximately 3-10 tons of fiber microplastics depositing annually in the region. Therefore, atmospheric deposition is an important source of microplastics in surface soils.

Surface Runoff and Irrigation Transport Microplastics into Soil Watershed irrigation, surface runoff, or infiltration are also pathways for microplastics to enter soil. Zhao et al. [34] found microplastic abundance in the Yangtze River estuary surface water reached 4,137.3$±2, 461.5particles/m^{\{3\}.DiandWang[35]foundmicroplasticabundanceof4,7}$ in the Chongqing-Yichang section of the Yangtze River. Large quantities of microplastics also exist along remote inland lake shores [36,37], and agricultural irrigation and surface runoff will transport these microplastics into soil. Additionally, sewage contains large amounts of microplastics [38]. Although sewage treatment plants process this water before discharge, microplastics are not completely removed due to their small particle size. Lares et al. [39] reported that after activated sludge and biofilm reactor treatment, water samples still contained 1.0 particles/L and 0.4 particles/L of microplastics, respectively. Gies et al. [40] estimated that at Vancouver’ s largest wastewater treatment plant, 97%-99% of microplastics were retained, but 30 billion microplastics were still released into the environment annually through effluent discharge. Domestic and industrial wastewater discharge enters soil through surface runoff or irrigation, causing microplastic accumulation.

Degradation and Environmental Risks of Microplastics in Soil Ecosystems

Degradation Characteristics of Microplastics in Soil Ecosystems Microplastics in soil undergo changes in polymer molecular chemical structure under the action of light, high-temperature oxidation, physical erosion, and biodegradation, including polymer molecular chain breakage, disproportionation, and increased surface oxygen-containing functional groups (such as ester and ketone groups). Zhou et al. [6] identified surface weathering of microplastics in tidal flats, finding not only polymer molecular chain breakage characteristics such as micropores and cracks on different microplastic surfaces, but also increased surface oxygen- and nitrogen-containing functional groups. For example, pyrolysis-gas chromatography-mass spectrometry analysis detected substances such as α-N-desmethylmethadol, 1,1-diphenyl-spiro[2,3]-hexane-5-carboxylic acid methyl ester, and octadecyl palmitate on weathered microplastic surfaces. Similar surface changes have also occurred on different types of tidal flat microplastics (LDPE, PET, PVC) [41]. These surface changes indicate that microplastics undergo degradation and can become smaller-sized microplastics or even nanoplastics.

However, compared to marine surface and tidal flat environments, degradation efficiency in soil is lower due to light shielding effects and low-oxidation conditions, leading to longer residence times. For example, only 0.4% of polypropylene (PP) plastic was degraded after one year in soil [42], while PVC plastic showed no degradation after 35 years in soil [43]. Recent research on degradation by terrestrial organisms has made significant progress. Yang et al. [44] found that mealworms (*Tenebrio molitor* Linnaeus) could consume polystyrene foam plastic. Further research on mealworm gut microorganisms identified intestinal bacterial strain YT2 (*Exiguobacterium* sp.) with the ability to degrade polystyrene foam plastic [45]. Bacteria capable of degrading low-density polyethylene plastic in soil have also been isolated from earthworm (*Lumbricus terrestris*) guts, including Gram-positive bacteria such as actinomycetes (*Microbacterium awajiense*, *Rhodococcus jostii*, *Mycobacterium vanbaalenii*, and *Streptomyces fulvissimus*) and firmicutes (*Bacillus simplex* and *Bacillus* sp.), with degradation products such as octadecane and docosane detected [46].

Migration and Environmental Risks of Microplastics in Soil Ecosystems After entering soil, microplastics migrate under the influence of plant root systems, biological and mechanical disturbance. Current research focuses more on microplastic migration driven by bioturbation. For example, earthworms (*L. terrestris*) in soil can transport more than 60% of polyethylene pellets from the surface layer to soil layers below 10 cm, with smaller particle sizes (710-850 μm) migrating more easily than larger ones [47]. Lwanga et al. [8] also showed that microplastics migrate to earthworm burrows, with earthworms exhibiting particle size selectivity in microplastic migration, where PE pellets <50 μm migrate more easily than larger particle sizes. In addition to earthworms, springtails *Folsomia candida* and *Proisotoma minuta* can also transport resin particles (100-200 μm) and fibers from surface soil to lower layers. Microplastic migration within soil driven by earthworms may affect soil aggregate structure and function, thereby influencing soil water and nutrient transport [8].

In addition to migrating within soil after disturbance, microplastics can also migrate out of soil through erosion and surface runoff into water bodies, and even further into marine environments [48]. Nizzetto et al. [49] used the INCA-Contaminants theoretical model to simulate, for the first time, the proportion of microplastics entering soil through sludge application that migrate to water bodies, using the Thames River basin in London as an example. They found that 16%-38% of microplastics remained in soil, while the majority eventually migrated from soil into water bodies, becoming a source of microplastic pollution in aquatic environments. Therefore, soil is not only a "sink" for microplastics but can also be a "source" of microplastics for water environments.

Bioaccumulation and Ecological and Food Chain Risks of Microplastics in Soil Ecosystems Research on bioaccumulation and toxic effects of microplastic exposure in soil ecosystems has just begun. Studies have found that earthworms (*L. terrestris*) can ingest and excrete microplastics, with excreted microplastics showing particle size selectivity—microplastics <50 μm are more easily excreted [50]. Earthworm growth was significantly inhibited and mortality increased significantly after exposure to high concentrations (>28%) of PE microplastics, though reproduction was unaffected. Research on another soil animal, *Folsomia candida*, found that exposure to PVC microplastic particles (80-250 μm) altered gut microbiota and significantly inhibited growth and reproduction, with changes in feeding behavior indicated by δ^{15}N and δ^{13}C values [51]. Microplastics in soil can also transfer and accumulate through food chains, posing health risks. Lwanga et al. [9] first reported microplastic transfer in backyard soil-earthworm and soil-chicken food chains, finding enrichment factors of 12.7 from soil to earthworm cast and up to 105 from soil to chicken feces. The study also observed microplastic accumulation in chicken gizzards, with an enrichment factor of 5.1. Since gizzards are commonly used as food, this exposure pathway warrants attention regarding human health impacts. Whether microplastics in soil can enter plants remains unreported. Qi et al. [52] studied the effects of low-density polyethylene (LDPE) and biodegradable plastic mulch film fragments on wheat growth, showing that both types of plastic film interfered with wheat growth, with biodegradable plastic film having a greater impact. Bandmann et al. [53] demonstrated through tobacco cell culture studies that nanoscale plastic microbeads could enter tobacco cells through endocytosis, indicating that small-sized nanoplastics may enter plants through root uptake, though this requires confirmation through plant cultivation experiments.

Future Research Directions and Risk Prevention Countermeasures

At the Second United Nations Environment Assembly in 2015, microplastic pollution, as an emerging environmental pollutant, was listed as the second largest scientific issue in environmental and ecological science research, becoming a major global environmental problem alongside climate change and ozone depletion. In China, the Ministry of Science and Technology launched the key special project "Marine MicroPlastic Monitoring and Ecological Environment Effects Assessment Technology" in 2016. Compared to marine ecosystems, microplastic pollution and its ecological, food chain, and health risks in soil and terrestrial ecosystems have not received sufficient attention. As the main unit and central hub for material exchange and energy conversion in Earth' s surface ecosystem, soil ecosystems play important roles in receiving microplastic pollution from surface systems and inputting microplastics to marine systems. Therefore, there is an urgent need to reveal the pollution patterns of microplastics in soil ecosystems, develop analysis, assessment, and remediation technologies, and provide scientific basis and technical support for microplastic pollution control in terrestrial ecosystems.

Establish and Improve Separation and Analysis Methods for Microplastics in Soil Due to the influence of soil texture, organic matter, and aggregate structure, separating and identifying microplastics from soil is more difficult than from water and sediment [24,54]. Current separation methods for soil microplastics mainly borrow from sediment microplastic separation methods, such as density separation [55] and flotation [56]. Recently, researchers have proposed using pressurized fluid extraction (PFE) for soil microplastic separation [7]. Although this method can quantitatively analyze microplastic content in complex matrices like soil, it cannot obtain physical information such as particle size, shape, and surface morphology of microplastics in samples. Other researchers have used visible-near infrared spectroscopy [56] and hyperspectral imaging combined with chemometrics [51] for rapid prediction and identification of microplastics in soil, but these methods still have limitations, such as narrow identification range and insufficient accuracy. Therefore, given the diversity of soil properties and the complexity of microplastic physical and chemical properties, methodological research on separation and identification of different microplastic types for various soil properties is necessary, and technical specifications should be established.

Assess the Releasability of Chemical Additives from Microplastics in Soil Environments to Prevent Environmental Risks Large quantities of additives are incorporated during plastic production and processing, such as plasticizers, flame retardants, antioxidants, and light/heat stabilizers. These chemicals are typically physically mixed into polymer structures and thus are easily released into the environment as new pollution sources. Zhang et al. [58] reported extracting multiple organophosphorus flame retardants and phthalates from tidal flat microplastic samples, with tris(chloroisopropyl) phosphate (TCPP) reaching up to 84.4 µg/g. Jang et al. [59] also detected hexabromocyclododecane (HBCDs) flame retardants in polystyrene foam plastic at concentrations up to 5,220 µg/g. Many flame retardants and plasticizers are toxic to humans: phthalates and bisphenol A have endocrine-disrupting effects, while chlorinated organophosphate flame retardants are carcinogenic. HBCDs are listed as new persistent organic pollutants due to their persistence and multiple toxicities including neurotoxicity and developmental toxicity. These loosely bound additives can be released into the environment under the influence of UV radiation, temperature, oxygen content, soil pH, and dissolved organic matter [57]. In marine environments, studies have found that polystyrene foam plastic can release HBCDs into the environment, which accumulate in mussels [59]. Therefore, the large presence of microplastics in soil environments will become an important source of chemical additive pollution, though the risks of microplastic-additive combined pollution to soil food chain safety, ecosystems, and human health have not yet been assessed. Future research should focus on the release patterns of microplastic chemical additives under different soil environmental conditions and evaluate their combined effects with microplastics on soil ecosystems, food chains, and human health.

Systematically Understand the Impact of Microplastic Pollution on Soil Functions and Develop Source Control and Environmental Degradation Remediation Technologies Although some studies have shown that microplastics have toxic effects on soil organisms such as earthworms and springtails and may transfer and accumulate through food chains, the range of species studied is still limited, and the obtained toxicity data are far from meeting exposure risk assessment requirements. Therefore, research combining soil ecosystem characteristics with actual microplastic pollution types should be conducted at multiple levels and scales under environmentally relevant concentrations, including: (1) establishing dose-effect relationships for microplastics in soil animals, plants, and microorganisms to provide basic data for establishing soil microplastic risk assessment methods and environmental criteria; (2) revealing the transfer and transformation patterns of microplastics and their surface-adsorbed chemical pollutants in soil ecosystems and food webs to understand pollution causes and provide scientific basis for ecological and food chain risk assessment; (3) clarifying the impacts of microplastic accumulation on soil physical, chemical, and biological properties, and analyzing the possibility of these impacts altering soil nutrient and pollutant biogeochemical cycles to assess damage to soil production and environmental purification functions; and (4) based on the above understanding and assessment, developing materials, methods, and technologies for source control and degradation remediation of microplastic pollution to construct a technical support system for soil microplastic pollution risk management and remediation.

References

1. Jambeck J R, Geyer R, Wilcox C, et al. Plastic waste inputs from land into the ocean. Science, 2015, 347: 768-771.
2. Rocha-Santos T, Duarte A C. 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, 2015, 65: 47-53.
3. Syberg K, Khan F R, Selck H, et al. Microplastics: Addressing ecological risk through lessons learned. Environmental Toxicology and Chemistry, 2015, 34: 945-953.
4. Zhou Q, Zhang H B, Li Y, et al. Research progress on microplastic pollution and its ecological effects in coastal environments. Chinese Science Bulletin, 2015, 60: 3210-3220.
5. Rillig M C. Microplastic in terrestrial ecosystems and the soil? Environmental Science and Technology, 2012, 46: 6453-6454.
6. Zhou Q, Zhang H B, Zhou Y, et al. Surface weathering and compositional changes of microplastics in coastal estuarine tidal flats. Chinese Science Bulletin, 2018, 63: 214-223.
7. Fuller S, Gautam A. A procedure for measuring microplastics using pressurized fluid extraction. Environmental Science and Technology, 2016, 50: 5774-5780.
8. Lwanga E H, Gertsen H, Gooren H, et al. Incorporation of microplastics from litter into burrows of Lumbricus terrestris. Environmental Pollution, 2017, 220: 523-531.
9. Lwanga E H, Vega J M, Quej V K, et al. Field evidence for transfer of plastic debris along a terrestrial food chain. Scientific Reports, 2017, 7(1): 14071.
10. Scheurer L, Bigalke M. Microplastics in Swiss floodplain soils. Environmental Science and Technology, 2018, 52(6): 3591-3598.
11. Zhou Q, Zhang H B, Fu C C, et al. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma, 2018, 322: 201-208.
12. Liu M, Lu S, Song Y, et al. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. Environmental Pollution, 2018, 242: 855-862.
13. Zhang G S, Liu Y F. The distribution of microplastics in soil aggregate fractions in southwestern China. Science of the Total Environment, 2018, 642: 12-20.
14. Mason S A, Garneau D, Sutton R, et al. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environmental Pollution, 2016, 218: 1045-1054.
15. Zubris K A V, Richards B K. Synthetic fibers as an indicator of land application of sludge. Environmental Pollution, 2005, 138: 201-211.
16. Mahon A M, O’ Connell B, Healy M G, et al. Microplastics in sewage sludge: Effects of treatment. Environmental Science and Technology, 2017, 51: 810-818.

17. Mintenig S M, Int Veen I, Loder M G J, et al. Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. Water Research, 2017, 108: 365-372.
18. Li X, Chen L, Mei Q, et al. Microplastics in sewage sludge from the wastewater treatment plants in China. Water Research, 2018, 142: 75.
19. Yang G, Zhang G, Wang H. Current state of sludge production, management, treatment and disposal in China. Water Research, 2015, 78: 60-73.
20. Yu J, Tian N N, Chen T B, et al. Analysis of application prospects of sludge agricultural utilization in sludge disposal in China. Water & Wastewater Engineering, 2010, 36(S1): 113-115.
21. Wu L, Cheng M, Li Z, et al. Major nutrients, heavy metals and PBDEs in soils after long-term sewage sludge application. Journal of Soils and Sediments, 2012, 12(4): 531-541.
22. Wang H, Liu R, Zhang M. Phytoremediation of cadmium and zinc from an agricultural soil contaminated with sewage sludge. International Journal of Phytoremediation, 2015, 17(6): 575-582.
23. Liu X, Liu W, Wang Q, et al. Soil properties and microbial ecology of a paddy field after repeated applications of domestic and industrial sewage sludges. Environmental Science and Pollution Research, 2017, 24(9): 8619-8628.
24. Bläsing M, Amelung W. Plastics in soil: Analytical methods and possible sources. Science of the Total Environment, 2018, 612: 422-435.
25. Gajst T. Analysis of Plastic Residues in Commercial Compost. Nova Gorica: University of Nova Gorica, 2016.
26. Weithmann N, Möller J N, Löder M G J, et al. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Science Advances, 2018, 4(4): eaap8060.
27. National Agricultural Technology Extension Service Center. Current status and development suggestions for organic fertilizer resource utilization. Soils and Fertilizers Sciences in China, 2010, (4): 77-82.
28. Zhao Y, Chen X G, Wen H J, et al. Research status and prospects of farmland residual film pollution control technology. Transactions of the Chinese Society of Agricultural Machinery, 2017, 48(6): 1-14.
29. Steinmetz Z, Wollmann C, Schaefer M, et al. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Science of the Total Environment, 2016, 550: 690-705.
30. Wang J, Luo Y, Teng Y, et al. Soil contamination by phthalate esters in Chinese intensive vegetable production systems with different modes of use of plastic film. Environmental Pollution, 2013, 180: 265-273.
31. Ramos L, Berenstein G, Hughes E A, et al. Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. Science of the Total Environment, 2015, 523: 74-81.
32. Zhou Q, Tian C G, Luo Y M. Discovery of multiple microplastics and their differential deposition fluxes in the atmospheric environment of coastal cities. Chinese Science Bulletin, 2017, 62: 3902-3909.

33. Dris R, Gasperi J, Saad M, et al. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Marine Pollution Bulletin, 2016, 104(1-2): 290-293.
34. Zhao S, Zhu L, Wang T, et al. Suspended microplastics in the surface water of the Yangtze estuary system, China: first observations on occurrence, distribution. Marine Pollution Bulletin, 2014, 86(1-2): 562-568.
35. Di M, Wang J. Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. Science of the Total Environment, 2018, 616: 1620-1627.
36. Free C M, Jensen O P, Mason S A, et al. High-levels of microplastic pollution in a large, remote, mountain lake. Marine Pollution Bulletin, 2014, 85(1): 156-163.
37. Zhang K, Su J, Xiong X, et al. Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China. Environmental Pollution, 2016, 219: 450-455.
38. Murphy F, Ewins C, Carbonnier F, et al. Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environmental Science and Technology, 2016, 50(11): 5800-5808.
39. Lares M, Ncibi M C, Sillanpää M, et al. Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. Water Research, 2018, 133: 236.
40. Gies E A, LeNoble J L, Noël M, et al. Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada. Marine Pollution Bulletin, 2018, 133, 553-561.
41. Zhou Q, Zhang H, Fu C, et al. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma, 2018, 322: 201-208.
42. Arkatkar A, Arutchelvi J, Bhaduri S, et al. Degradation of unpretreated and thermally pretreated polypropylene by soil consortia. International Biodeterioration and Biodegradation, 2009, 63(1): 106-111.
43. Ali M I, Ahmed S, Robson G, et al. Isolation and molecular characterization of polyvinyl chloride (PVC) plastic degrading fungal isolates. Journal of Basic Microbiology, 2014, 54(1): 18-27.
44. Yang Y, Yang J, Wu W M, et al. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 1. Chemical and physical characterization and isotopic tests. Environmental Science and Technology, 2015, 49(20): 12080-12086.
45. Yang Y, Yang J, Wu W M, et al. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 2. Role of gut microorganisms. Environmental Science and Technology, 2015, 49(20): 12087-12093.
46. Lwanga E H, Thapa B, Yang X, et al. Decay of low-density polyethylene by bacteria extracted from earthworm' s guts: A potential for soil restoration. Science of the Total Environment, 2018, 624: 753-757.
47. Rillig M C, Ziersch L, Hempel S. Microplastic transport in soil by earthworms. Scientific Reports, 2017, 7(1): 1362.
48. Horton A A, Walton A, Spurgeon D J, et al. Microplastics in freshwa-

ter and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Science of the Total Environment, 2017, 586: 127-141.

49. Nizzetto L, Bussi G, Futter M N, et al. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environmental Science: Processes and Impacts, 2016, 18(8): 1050-1059.
50. Lwanga E H, Gertsen H, Gooren H, et al. Microplastics in the terrestrial ecosystem: implications for Lumbricus terrestris (Oligochaeta, Lumbricidae). Environmental Science and Technology, 2016, 50(5): 2685-2691.
51. Zhu D, Chen Q L, An X L, et al. Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. Soil Biology and Biochemistry, 2018, 116: 302-310.
52. Qi Y, Yang X, Pelaez A M, et al. Macro-and micro-plastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth. Science of the Total Environment, 2018, 645: 1048-1056.
53. Bandmann V, Müller J D, Köhler T, et al. Uptake of fluorescent nano beads into BY2-cells involves clathrin-dependent and clathrin-independent endocytosis. FEBS Letters, 2012, 586(20): 3626-3632.
54. de Souza Machado A A, Kloas W, Zarfl C, et al. Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology, 2018, 24(4): 1405-1416.
55. Hidalgo-Ruz V, Gutow L, Thompson R C, et al. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science and Technology, 2012, 46(6): 3060-3075.
56. Zhou Q, Zhang H B, Zhou Y, et al. Separation of microplastics from coastal tidal flat soils and their surface microscopic characteristics. Chinese Science Bulletin, 2016, 61(14): 1604-1611.
57. Ren X W, Tang J C, Yu C, et al. Research progress on soil microplastic pollution and ecological effects. Journal of Agro-Environment Science, 2018, 37(6): 1045-1058.
58. Zhang H, Zhou Q, Xie Z, et al. Occurrences of organophosphorus esters and phthalates in the microplastics from the coastal beaches in north China. Science of the Total Environment, 2018, 616: 1505-1512.
59. Jang M, Shim W J, Han G M, et al. Formation of hazardous chemicals from beached plastics. Environmental Science and Technology, 2016, 50(10): 4951-4960.

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