Microplastics in Soil Ecosystem: Insight on Its Fate and Impacts on Soil Quality

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Contents

Abstract Plastic film has been intensively used in (semi-)arid agricultural regions, attributing to its great benefits of improving soil productivity and crop yield in

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China. However, plastic debris, as a consequence of film mulching, remains and accumulates in soil leading to severe soil quality problems, as well as environmental concerns especially the small fragmented particles referred to as microplastics (MPs). Though increasing attention has been aroused for MPs in the aquatic environment, the knowledge of MPs' behavior and its effects on soil quality is extremely insufficient and urgently needed. In this study, we oriented the benefits of plastic film use, its contribution to agriculture productivity, and the effects of MPs on soil properties and its related soil quality indicators. Admittedly, the increasing trend of using plastic film made by light density of polyethylene would be continued in China, and the pieces of plastic particles would either be persistent and accumulated in soil layers or be slowly aging and degraded. The impacts of MPs on soil quality need more attention due to the limited studies available focusing on its fate and interactions associated with soil ecosystem services and environmental resilience. Although policies and agricultural extending services on plastic film application have been laughed for a few years, alternative materials used for producing environment-friendly film, plastic debris recycling, and solutions on pieced particle removal are the great challenges for sustainable farming. Thus, it is urgent to understand MPs' effects on soil quality which is crucial for soil-plant system and soil pollution monitoring and prevention.

Keywords Microplastics, Plastic film mulching, Risk assessment, Soil quality, Terrestrial ecosystem

1 Introduction

Plastic mulching, a promising farming technic, has been widely used attributing to its benefits for increasing crop yields in arid and semiarid areas [1, 2]. However, the presence of plastic residues has become a challenging problem for soil quality and the environment, especially small plastic particles, such as macro-, micro-, and even nanoplastic residues which are potentially harmful for agroecosystems [3] and surroundings delivered by erosion or runoff [4]. There are numbers of study that focus on microplastics in marine [5], coastal tidal flats [6], estuaries [7], lakes [8], and other water ecosystems [9] but less on the impact of soil ecosystems.

MPs in the soil environment include application of sewage sludge, flooding and street runoff, plastic litter, atmospheric fallout, landfill, and plastic film mulching [10]. The application of sewage sludge to arable land alone could add an annual MPs load to soil greater than that entering the world's oceans [11]. Although sewage sludge application has been banned in some countries, the application of compost and the use of plastic foil in agriculture become the new MPs sources to contaminate soil [10, 12]. Industrial plastics, littering, road dust, diffuse atmospheric deposition, sedimentation from water flooding, and irrigation are other sources of MPs in the environment, but the quantity and its effects in soil are still not well-reported. Nizzetto et al. [11] estimated that around 430,000–63,000 and 300,000–44,000 tons of MPs are input annually into farmlands in Europe and North America, respectively. Landfill contributes 30.8% of 25.8 million tons of postconsumer plastics becoming airborne small particles (e.g., MPs) [13]. Furthermore, since plastic mulching is used widely in dryland area, plastic fragments from larger pieces to microparticles, as a consequence of mulching, continuously accumulate in soil and become the severe problems to soil quality and its surrounding ecological environment.

After entering into the soil, plastics will interact with pollutants in the soil, which will affect the environmental behavior and create environmental effects in the soil, as well as soil properties. MPs in soil can adsorb with other pollutants such as persistent organic pollutants (POPs) and heavy metals, which make them more harmful in the long term [14]. This adsorption includes physical adsorption and chemical adsorption. Physical adsorption is the action between adsorbate and adsorbent under van der Waals force, which mainly depends on the specific surface area [15]. The adsorption properties of MP particles is related to their own characteristics, such as material, specific surface area, amount of adsorption sites on the surface, and hydrophobicity [16]. The source and age of MPs also have a certain influence on their adsorption, and different environmental conditions, such as pH, salinity, and metal cation concentrations can also affect the adsorption properties of MPs. Polyethylene (white, diameter $\sim$4 mm, mass $\sim$25 mg) adsorbed with metal elements (Al, Fe, Mn) and trace metal elements (Cu, Zn, Co, Cr, Mo, Sb, Sn, Pb, Ag, Cd, U) and the adsorption mechanism may be direct adsorption of metal cation, metal ions collide with charged or neutral regions of plastic surfaces, and adsorption or co-precipitation with iron-manganese oxide [15]. Hence, MPs presence in soil would alter the elements' bioavailability affecting either soil functions or compounds' environmental behaviors.

Furthermore, MPs content in soil is likely unavoidable to affect soil organisms and decrease soil fertility and thus alter soil ecological function and global food production. Despite direct uptake of MPs by crops and transferring MPs to edible plant parts seeming unlikely, MPs could enter into the human food chain by animals and livestock [17]. Many animals are unable to digest the plastic fragments, thus preventing food from passing through the gut, but soil fauna, and especially earthworms, can digest MPs by crushing fragile plastic fragments [18]. Earthworms and other soil micro-animals are indispensable members in the soil environment, and they play an important role in transportation and transformation of MPs which, in turn, influence soil biological function to decompose organic matter. Furthermore, microbial communities on plastic debris are seen as the "plastisphere" [19, 20]. Zettler et al. (2013) found that the average plastisphere abundance was lower than that of surrounding microorganisms, while the homogeneity among communities was greater. Bacterial community on the plastic substrate has obvious discrepancies from that in the surroundings [21]. Correspondingly, the contribution of plastisphere on the surface of MPs is significant to the degradation process [22, 23]. It is reported that polycaprolactone could be degraded by impure and pure cultures of germs and *Saccharomycopsis* [24]. Moreover, *Comamonas acidovorans* TB-35 took advantage of polyester polyurethane as the single carbon source and produced a polyester polyurethane-degrading enzyme [25]. As a consequence, the micromolecular water-soluble intermediates are absorbed by the cells and enter a special metabolism which might affect soil microbial communities and volatile compounds. The enhancement of microbial activity increases extracellular enzyme secretion and promotes the release of nutrients such as C, N, and P in soil, thus promoting the migration of nutrients between plants and soil [26, 27]. Meanwhile, many additives, such as stabilizers and plasticizers, added to plastic during manufacturing to increase the durability, are released during exposure and become bioavailable to soil organisms, thus threating soil quality [28–30]. These concerns and on the presence of MPs in soil and their interaction with soil quality indicators are still a large gap in current knowledge for our understanding of MPs pollution in agricultural soil and terrestrial ecosystem.

Therefore, the scope of this chapter is to address plastic film mulching and debris of soil quality related aspects that lead to soil degradation and environmental problems. Our aim is to screen current situation of plastic film mulching and its consequences on soil quality which are not well-concerned and even not recognized. Based on the background information of plastic film mulching, implications are provided for anticipating MPs abundance that may aggravate soil quality.

2 Plastic Film Application and Its Residues

2.1 Plastic Film Application

In China, plastic film has been tremendously used in agriculture especially in dryland areas since imported from Japan in the 1970s. The quantity of plastic film application has been increased around two times from 1999 to 2016, reaching 2.60 million tons and mulching farming land 1.84×10^6 ha [31]. Great benefits of plastic film application have been achieved for crop yields and economic returns [32], and its advantages for farming can be mainly highlighted as four aspects:

1. Soil temperature and soil physical properties. After plastic film mulching, soil temperature increases [33, 34], and vapor pressure effects lead to soil porosity and soil aggregate stability increasing and bulk density declining [35, 36]. These properties are either good for seed germination, seedling emergence [37], and root growing [38] or water-heat balances inside of soil under mulching. Due to soil surface mulching, raindrop-induced soil detachment and erosion have been reduced [39], as well as avoiding soil compaction during the whole plant growing seasons.
2. Soil water conservation. Soil moisture could increase by plastic mulching [40, 41], varied by different mulching schemes shown in Fig. 1. It is reported that rain-harvesting efficiency improved significantly (65.7–82.7%) with the film fully mulched ridge-furrow water harvesting scheme in maize growing seasons

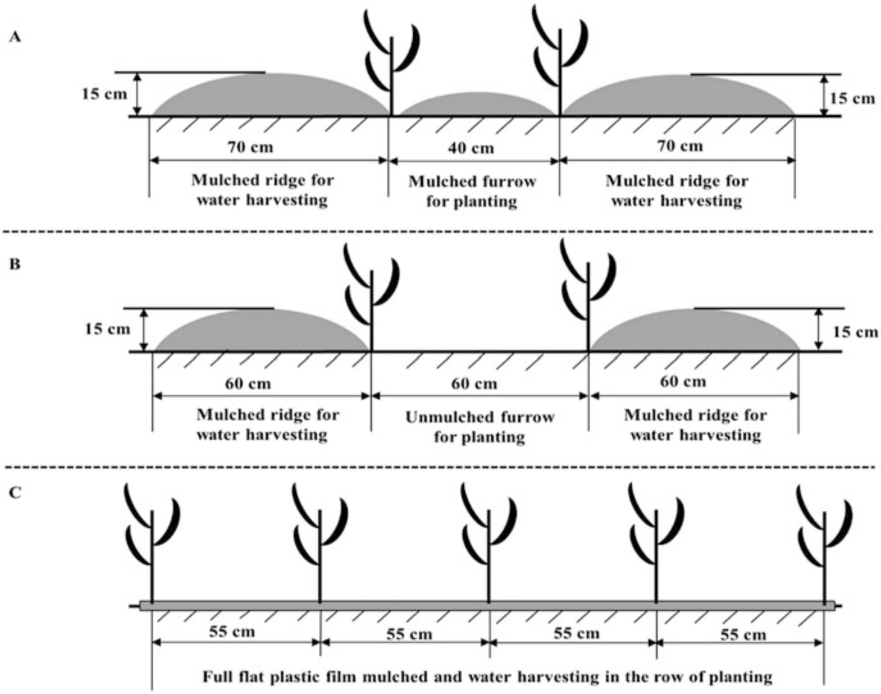

Fig. 1 The three main plastic film mulching schemes ((**a**) full ridge-furrow mulching; (**b**) half mulching; (**c**) full flat mulching) in the field for crop planting and water harvesting

[42]. Meanwhile, due to the plastic mulching, soil surface evaporation rate decreases [1], and average soil water storage (750–1,500 m^3 ha^{-2}) and the infiltration depth of soil water in dryland increased significantly, which result in high potential productivity and crop yields [43].

3. Nutrients cycling and soil microbial activities. Nutrients availability accelerates attributing to the soil temperature and water thermodynamic changes [44]. Meanwhile, the covered soil surface avoids nutrients loss by leaching, runoff, and erosion of sediment [45]. Studies indicated that soil available N, P, and K might increase [46]. Due to the positive impacts on soil temperature and soil water storage, plastic mulching is beneficial for soil microbial activities and organic matter decomposition and mineralization [47–49] which contributes to nutrients cycling and plant growth.
4. Weeds control. Concerning the large scale of farming land in NW China being covered by plastic film, weeds sprout and growing are inhibited, as well as soilborne diseases and pests due to high soil temperature. Then agrochemical products for weeds control are greatly reduced which avoids soil contamination and compounds residues threatening soil quality and food safety.
5. In addition, as a promising agriculture water-saving technique, plastic mulching combined with drip irrigation and different mulching patterns has been expanded

to the irrigation regions which used to be abandoned dryland or water-limited land, and can save water of 6,000–15,000 m^3 ha^{-2}: the growing degree day increasing (200–400°C), the latitude going northward (2–5°), and the altitude arising (500–1,000 m). Therefore, with great benefits achieving from plastic film application, it is no doubt that plastic film would be continuously used for water and energy consumptions in the agriculture, especially in dryland area [50].

2.2 Plastic Residues

With quantity of plastic film used continuously, plastic residue, as a consequence of plastic film application, has become the big challenge of environment problems, especially in the areas with long-term plastic film use [51]. As it is mentioned above, due to the high efficiency of harvesting water and crop yields, full ridge-furrow plastic mulching scheme in dryland regions has been widely extended [52], but plastic film is easily broken into pieces after harvesting either by weather conditions or by harvesting and plowing machines. It is reported the residues ranged from 50 to 260 kg hm^{-2} in arable lands after 10 years of plastic mulching [53] and the quantity of its accumulation pieces keeps increasing in farming soil layers and field surroundings (Fig. 2).

With regard to the regulations for the production of plastic film for farming, such as its thickness and its original materials, the regulation entitled GB13735-92 has been issued which changed the standard thickness to 0.01–0.02 mm instead of 0.008 ± 0.003 [54]. However, the material used to produce plastic film is mainly polyethylene with low-density and transparent properties associated with lower costs and higher yields to farmers [55]. This type of material with additives can be strengthened films but it is fragile to be pieced physically either by plants or by harvesting machines which thousands of plastic pieces formed and left in soil after harvesting. Comparing the weight of mulch film, around 60% of plastic residue is recycled [56], but the efficiency of recycling is limited, especially recycled by machines or by farmer themselves (Fig. 3). However, machine-supported recycling

Fig. 2 Plastic debris in soil layers and field surroundings (from Tinglu Fan)

Fig. 3 Plastic collection by machine and famers (from Tinglu Fan)

or farmer manually supported recycling only can remove larger pieces of plastic film, while small pieces, such as particles less than centimeters and even invisible, remain in soil which strongly impacts soil functions in the long-term farming [57].

Concerning the materials of plastic film using in farming, the fate of plastic debris after harvesting refers to aging and degradation in soil ecosystem. However, plastic aging is a long-term process associated with weather conditions and its original materials including additives [58]. Polyethylene, the most common polymer used to produce films, seems difficult to be aged by solar radiation, temperature, precipitation, and other physically based practices. Due to the larger plastic debris recycled, the smaller residuals, such as mega-, macro-, and microplastics, are either fragmented and accumulated or slowly degraded and involved into soil physiochemical processes and microbial activities [59, 60]. Although the quantity and risks of larger pieces of plastic debris have been intensively studied in cropping system [32], the abundance, distribution, and the environmental consequences of microscopic debris are only highlighted in near few years [61]. Meanwhile, plastic particles clustered in different soil layers depend on intensive plastic film use, mulching schemes, and cropping systems. According to our recent survey, macroplastics are concentrated in 0–10 cm soil layer, while MPs were mainly detected in 20–30 cm soil layers with a 30-year history of mulching (data not published). Therefore, it is urgent to concern a broad range of plastic particle types from mega- to micro- even to nanoplastics in the soil, and understand long-term effects of plastic particles on soil functions and quality [62].

3 Impacts of Microplastics on Soil Quality

3.1 Effects of Microplastics on Soil Physiochemical Properties

Although MPs have been detailed in aquatic systems, few studies have been done to illustrate its impacts on soil physical and chemical properties. Regarding MPs fragmentation and its fate in soil, it easily affects soil bulk density and water content, in accordance with the studies focusing on larger plastic residues which significantly reduced gravimetric soil water content and bulk density, decreased macropores, and altered soil water distribution [63]. Although the quantity of MPs may contribute greatly in soil, its effects on soil bulk density and porosity might be varied among different soil types [60]. Furthermore, comparing to soil without MPs contamination, soil saturated hydraulic conductivity, field capacity, and soil water repellency changed slightly but significantly increased in the treatment of relevant concentrations with 2% MPs addition [64]. If the abundance of MPs reaches a certain level, soil water characteristic curves could be shifted easily with the interaction of plastic aging and soil pore changes which potentially influence soil water availability and plant growth.

MPs significantly increased the nutrient contents of the soil dissolved organic matter, such as dissolved organic carbon (DOM), dissolved organic nitrogen, ammonium nitrogen, dissolved organic phosphorous, and phosphate [27, 65]. Liu et al. [27] found that the MPs addition led to the accumulation of high-molecular-weight humic-like materials and fulvic acid indicating that the decomposition rate of humic-like material after MPs addition was slowed and more DOM accumulated. In this case, if these compounds accumulate in soil, the sources for soil microbial activities and nutrient bioavailability for plants seem to be constrained. Meanwhile, the effect of MPs on soil iron exchanges is related to it being monovalent or multivalent. Similar as clay particles, MPs could be adsorbed with mineral and organic surfaces and surface groups but different from cations, such as Ca^{2+}, Fe^{3+}, and Al^{3+} potentially affecting the adsorption or exchange position for pollutants, such as pesticides and persistent organic pollutants [66]. Thus, further researches are needed to understand MPs effects on soil physicochemical properties, especially soil types with abundance of irons and clay particles.

3.2 Effects of Microplastics on Soil Biota

Diversity of soil animals plays an important role either for soil formation or for soil functions, especially earthworm abundance defined as a biological indicator to assess soil quality [67]. MPs integrated with soil particles could be ingested by soil meso- and microfauna and thus have the potential to bioaccumulate in the food chain [68]. Earthworms exposed to MPs showed that the growth and survival rate of earthworms were negatively affected [69] indicating that MPs in the environment potentially affect soil organisms. Earthworms acted as a transport vector of MPs in soil, incorporating material into soil via casts, burrows, and adherence to the earthworm's exterior leading to the potential risks of exposure for other soil biota communities [70, 71]. It is reported that with the MPs addition, the kinetics of glyphosate changed slightly [66] but the quantity of transport of glyphosate was influenced by the combination of glyphosate and MPs [72].

Soil microbial communities have a crucial role in nutrients cycling and influence pollutant behavior, including the mineralization, biodegradation, and detoxification of toxic compounds [73, 74]. Previous studies showed that soil microbial respiration and soil β-glucosidase, urease, and phosphatase concentrations significantly varied with the addition of high MPs content. Liu et al. [27] reported that MPs stimulated enzymatic activity and activated organic C, N, and P which were useful for the accumulation of dissolved organic C, N, and P. Furthermore, extracellular enzymes produced by micrograms are excreted and attached to the MPs surface during the degradation process. As a consequence, the micromolecular water-soluble intermediates are absorbed by the cells and enter a special metabolism which probably alters soil microbe communities [23]. In addition, concerning the polymer used for plastic film production, its residues degraded in soil might release C which can be a source for soil microbial activities and also beneficial for soil functions. Although degradation rate of plastic particles is limited and slow, the C source contribution to soil quality still needs to be studied in further research.

4 Implications and Conclusion

It is widely understood that the pressure of plastic film residues on agricultural sustainable development can be detrimental, both environmentally and to farmland productivity. However, plastic mulching combined with water harvesting technics is continuously used and extended in order to produce enough food and economic values in dryland area. With the long-term plastic film application, hence, abundance of MPs and other plastic particles increases, and they accumulate gradually in soil layers. Although it can be transported by surface runoff and leaching via soil pores, it would strongly affect soil properties and soil functions. Meanwhile, due to the interaction with soil particles and soil microbe, coupled contamination with other pollutants needs to be taken into account, and it needs more efforts to replace current low-density plastic film with alternative materials. Some bacteria isolated from worm gut could digest plastic particles [18, 75], but the efficiency and application condition remain unclear. Despite plastic debris in soil being difficult to clean, some policies can be made to prevent such “white pollution.” Unfortunately, there are a number of barriers to the design and implementation of policies to relieve these pressures and to improve the supervision and recycling systems. These barriers include the difficulties of accessing alternative materials to produce environment-friendly and cheaper plastic film and deploying the machines to recycle the residues after harvesting. Furthermore, local economic development enhanced by plastic mulching market leads to policies lack of support by local government and farmer themselves. Although subsidies have been approved for farmers or commercial companies to recycle plastic debris, labor-consuming and huge investment to reuse such debris lead to lower recycle rate. Therefore, a new approach needs to be concerned and designed involving all stakeholders to reduce or eliminate plastic pollution, especially MPs risks on soil quality.

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