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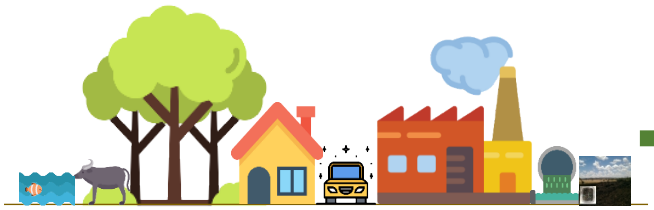
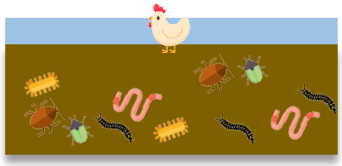


Dissemination of MPs in the environment
(Pharmaceuticals, Transportation,
Agriculture, Compost)



Effect of MPs on soil environment
(Plants, Animals and Microbes)

Isolation of MPs from the soil
(Sieving, Density separation,
Filtration and Extraction)

- Identification and characterization of MPs
- Assessment of ecological potential risks

Abstract

Microplastics (MPs) as emerging persistent pollutants have been a growing global concern. Although MPs are extensively studied in aquatic systems, their presence and fate in agricultural systems are not fully understood. In the agricultural soils, major causes of MPs pollution include application of biosolids and compost, wastewater irrigation, mulching film, polymer-based fertilizers and pesticides, and atmospheric deposition. The fate and dispersion of MPs in the soil environment are mainly associated with the soil characteristics, cultivation practices, and diversity of soil biota. Although there is emerging pollution of MPs in the soil environment, no standardized detection and quantification techniques are available. This study comprehensively reviews the sources, fate, and dispersion of MPs in the soil environment, discusses the interactions and effects of MPs on soil biota, and highlights the recent advancements in detection and quantification methods of MPs. The prospects for future research include biomagnification potency, cytotoxic effects on human/animals, nonlinear behavior in the soil environment, standardized analytical methods, best management practices, and global policies in the agricultural industry for the sake of sustainable development.

Keywords: Environmental pollution; Microplastics; Analytical techniques; Agricultural systems; Soil health; Sustainable development.

1. Introduction

In recent years, anthropogenic activities are considered as the key drivers of biodiversity loss and ecosystem functions (**de Souza Machado et al., 2018a**). A typical marker of human activity is the overwhelming amount of plastics produced and used. Plastics are chemically miscellaneous groups of synthetic polymeric materials with multiple applications in modern lifestyle (**Galloway**

45 **et al., 2017**). It has been estimated that the majority of the produced plastics (>80%) are
46 thermoplastics, which are industrialized via polymerization to form high-molecular-weight
47 polymers from low-molecular-weight monomers (**de Souza Machado et al., 2018a**). Their
48 physical and chemical characteristics can be altered and strengthened by physical methods (e.g.,
49 extrusion, melting, and palletization) and chemical methods (e.g., mixing with antioxidants,
50 copolymer polycarbonate, plasticizers, and colorants) (**Bittner et al., 2014**). As a result, plastic
51 materials have a strong physical structure along with complex chemical properties. Owing to low
52 cost, efficient malleability and durability, the demand and usage of plastics have been increasing
53 continuously in the past decades (**PlasticsEurope, 2015**), and 8300 of plastics are generated
54 worldwide (**Geyer et al., 2017**).

55 In 2016, 27.1 million metric tons (Mt) of plastic wastes were collected in the European Union
56 (EU), of which 31.1% were recycled, 41.6% were used for energy recovery, and the remaining
57 27.3% were disposed of at landfill sites (**PlasticsEurope, 2018**). It was estimated that the
58 contemporary manufacturing and waste management strategies would lead to 12,000 Mt of plastic
59 wastes in landfills/natural setting by 2050 worldwide (**Geyer et al., 2017**). As shown in **Table 1**,
60 the European plastic demand was ~47.8 Mt in 2014; however, only 54% and 16% (approximately)
61 of plastics underwent the waste management process and recycling system, respectively
62 (**PlasticsEurope, 2015**). More recently, 64.4 Mt of plastics production was reported in the EU,
63 while 8.4 Mt of plastic wastes were collected and recycled inside/outside the EU (**PlasticsEurope,**
64 **2018**). The worldwide plastic recovery and recycling rates might be even lower. It was found that
65 approximately 32% of plastic wastes might be present in the soil environment (**de Souza Machado**
66 **et al., 2018b; Jambeck et al., 2015**). Plastic wastes exposed to the natural environment can

undergo weathering processes such as degradation and disintegration due to the collective actions of physio-chemical and biological factors (**de Souza Machado et al., 2018a; Whitacre, 2014**).

Plastics waste including biodegradable plastics are actually more susceptible to physical disintegration (fragmentation) than degradation (mineralization), which result in smaller sizes of plastics **(Whitacre et al., 2014)**. The generated plastics with particle size <5 mm are generally considered as microplastics (MPs) (**Li et al., 2018**). The global presence of MPs is probably due to the extensive production of microplastic particles (e.g., microbeads) for diverse applications. Natural disintegration and degradation of MPs can also generate plastic particles <0.1 μm in size, which is known as nanoplastics (NPs) (**de Souza Machado et al., 2018a**). Owing to the deleterious effect of MPs on the marine and shoreline environment, MPs have attracted a lot of attention of marine scientists (**Galloway et al., 2017; Li et al., 2018; Wang et al., 2019**). Similar effects of MPs are also observed in freshwater and estuarine ecosystems (**Horton et al., 2017a**), and there also are emerging concerns over MPs as pollutants in the aquatic environments (**Li et al., 2018**).

MPs pollution in the soil environment has received nominal scientific attention in comparison to that of marine environment, whereas the former might be 4-23 times larger than the latter in terms of mass (**Horton et al., 2017b**). Terrestrial soil tends to accumulate more MPs than aquatic ecosystems (**Nizzetto et al., 2016a**). The United Nations Environment Programme (UNEP) identified that large quantities of particulate plastics found within the marine environment globally result from the land-based sources (**UNEP, 2016**). According to **Jambeck et al. (2015)**, 4.8 to 12.7 Mt of terrestrial plastic wastes enter the ocean annually, equivalent to 1.7 to 4.6% of the total plastic wastes generated worldwide. Sediment transfer during soil erosion is a process that allows the transport of particulate plastics from terrestrial to aquatic ecosystems. Despite this linkage to

terrestrial sources, most scientific investigations on plastic particles have neglected their effects (**Bolan and Bradney, 2019; Bradney et al., 2019**).

MPs pollution threats to the aquatic environments are frequently associated with the living organisms in the aquatic environments, i.e., MPs can serve as particulate matter for ingestion (**Rehse et al., 2016**), solid supports for pollutant transport (**Zhan et al., 2016**), and significant chances of physical injury during the movement (**de Souza Machado et al., 2018a**). The environmental impacts of MPs pollution in the agricultural soils may be underestimated in comparison to aquatic systems. Investigations are urgently required to draw attention to MPs in the agricultural systems. However, only a few recent studies have examined the pollution levels and the possible sources of MPs in the agricultural environment and their harmful effects on the soil biota (**Boots et al., 2019; Chae and An, 2018; Mai et al., 2018; Zhang & Liu, 2018; Zhang et al., 2018b**). Recent results revealed the pervasive and persistent nature of MPs in the soil environment (**Zhang & Liu, 2018**), and adverse effects of MPs on growth, reproduction, feeding, survival, and immunity level of the soil biota (animals, plants, and microorganisms) (**Zhu et al., 2018a; Zhu et al., 2019; Zhang et al., 2019**). The latest reviews came to describe the mechanisms and behavior of MPs in the soil environment (**Qi et al., 2020**), their biomagnification tendency via food chains, toxicological effects on soil microorganisms, and analytical methods (**Guo et al., 2020; Li et al., 2020**). Nevertheless, overall research on MPs pollution in agricultural soils is still in an embryonic stage and there are many knowledge gaps in this research areas. Several key questions such as pollution levels, ecological threats, dispersion mechanisms, and development in analytical and quantification technologies still require further studies in view of the high complexity and heterogeneity of the soil environment in different agricultural systems.

Therefore, this review aims to offer in-depth current knowledge about sources, fate, and dispersion mechanisms of MPs in the agricultural soils. The adverse effects of MPs of the soil flora and fauna are elucidated. This review also elaborates the analytical technologies involved in detection and quantification of MPs in soil and suggests the framework for future research.

2. Possible sources and dispersion mechanism of MPs in soil and agricultural environment

An enormous variety and range of MPs particles are available in the soil environment due to over exploitation of plastics and their unplanned management practices **(Figure 1)**. Typically, the existing literature reported that terrestrial environments are the only component of the natural systems that can act as a source and distribution pathway of MPs to the aquatic environments (**Horton et al. 2017a; Karbalaei et al., 2018; Lechner et al., 2014**). For example, the release of significant quantities of illegal commercial MPs from manufacturing plants to Reverse Danube has been reported (**Lechner et al., 2014**). Plastics near coastal zones or in surface water disintegrate due to direct physical abrasion and UV-sunlight. Nevertheless, both processes are marginal in the soil environment in which plastic disintegration and degradation could be comparatively slow (**Karbalaei et al., 2018**).

Previous investigations reported limited degradation of commercial polymers in the soil environment. **Arkatkar et al. (2009)** reported only 0.4% degradation of polypropylene (PP) after one-year soil incubation, while no weight loss was observed in the case of polyvinyl chloride (PVC) after soil incubation for 10-35 years. Soil texture and composition play vital roles in the degradation of synthetic polymers in the soil environment. It was reported that clayey soils showed a greater degradation of polymers in comparison to sandy soils, possibly attributed to a higher soil organic matter (SOM) **(César et al., 2009)**. There were also significant impacts of MPs on soil

134 and soil-water relation including water holding capacity, bulk density of soil, microbial activities,
135 and soil structure (**de Souza Machado et al., 2018a; 2019)**. The alteration in soil structure may
136 lead to changes in the microbial composition of the soil, although it can be difficult to predict such
137 changes (**Rillig et al., 2019**). The decrease in bulk density of the soil due to MPs pollution may
138 increase the rate of evaporation, thus significantly affecting plants growth (**Wan et al., 2019**).
139 Nevertheless, MPs pollution may also have some positive impacts on the soil properties. For
140 instance, MPs facilitated soil aeration and root penetration by reducing the bulk density of the soil
141 (**de Souza Machado et al., 2018a, Rillig et al., 2019**) and promoted the growth of onion bulbs
142 and roots resulting in the increase in total crop biomass (**de Souza Machado et al., 2019**).

143 There are several factors affecting the quantity of MPs deposition, retention, and transport in
144 the soil environment, such as anthropogenic activities (e.g., inefficient waste management
145 practices and littering), physical characteristics of plastic particles (e.g., form, size, and density),
146 climatic conditions (e.g., rainfall intensity and wind speed), and topography (**He et al., 2018b;**
147 **Karbalaei et al., 2018; O'Connor et al., 2019**). A substantial direct contribution of primary MPs
148 to terrestrial systems has been introduced via areal deposition of MPs. Synthetic textile fibers, wear
149 and tear from synthetic rubber tires, and city dust are the major atmospheric sources of particulate
150 plastics (**Kole et al., 2017; Löhr et al., 2017**). These particulate plastics are dispersed by wind in
151 the form of atmospheric pollution. For example, 3–7% of the particulate matter ($PM_{2.5}$) in the
152 atmosphere is estimated to consist of plastic derived from tire wear and tear (**Kole et al., 2017**).

153 Other sources of MPs in terrestrial environments include domestic wastes, personal care
154 products, mismanaged solid waste landfills, and land application of biosolids (**Horton et al.**
155 **2017b; Steinmetz et al. 2016; Rillig et al., 2017**). In developed countries, landfill sites are
156 enclosed by fences and dumped wastes are typically shielded with soil cover or synthetic materials,

157 which help to restrict the run-off of MPs from the site. Nevertheless, proper waste management
158 practices are in their infancy in developing or underdeveloped countries (**Duis & Coors, 2016**). A
159 substantial accumulation of plastic wastes in the agricultural soils has been reported in several
160 tropical and subtropical countries, with MPs from municipal wastes dumped in open agricultural
161 fields, parks, or landfill sites. **Lwanga et al. (2016)** reported that approximately 1000-4000 MPs
162 particles per kg of dry weight of biosolids were found in agrarian fields and dumping sites in
163 Europe; **Fuller & Gautam (2016)** reported MPs found in different types of soil close to a
164 commercial zone in Australia (**Table 2**). According to **Nizzetto et al. (2016b)**, due to the
165 application of biosolids as fertilizer, up to 700,000 tons of MPs may enter agricultural fields
166 annually in North America and Europe.

167 Properly designed and operated wastewater treatment plants (WWTPs) are able to effectively
168 remove MPs debris up to 99.9% from the wastewater streams, but a substantial quantity of MPs
169 remained in the biosolids (**Gies et al., 2018; Mintenig et al., 2017; Prata, 2018**). According to
170 **Alvarenga et al. (2016)**, more than 87% of the generated biosolids from wastewater treatment was
171 applied in the agriculture fields of Portugal in the form of composts or raw biosolids. Also, 4 to 5
172 Mt of sludge solids are used as fertilizer in the European Union (EU) every year in agricultural
173 lands. In some sites, commercial polymeric fibers were detected after five years of land application
174 of biosolids. Compost application in agriculture field is also considered a significant contributor
175 of plastics in soils. Although large- and medium-sized plastic fragments are mostly separated from
176 the composts (**Figure 2)**, minor quantity of smaller fragments formed during the process of
177 composting (milling process) remains in the form of secondary MPs or NPs (**Bolan and Bradney,**
178 **2019**). Polymer-based slow-release fertilizers (**Weithmann et al., 2018**) and pesticides (**Wang et**
179 **al., 2019**) along with the weathering of plastic film mulch used over agricultural fields also result

in the MPs pollution in the soil environment (**Huang et al., 2020; Ramos et al., 2015; Rillig, 2012**).

Personal care products (PCPs) such as gels, hand wash, shampoos, and facial cleaners are considered as the potential contributors of MPs and reach terrestrial environments via the application of biosolids and composts (**Alvarenga et al., 2016; Duis & Coors, 2016**). Polyester (PES), polystyrene (PS), and melamine are applied in different industries as abrasive materials, which are the potential sources of MPs. Other contributors of primary MPs including plastic powder and plastic resin pellets can enter the terrestrial environments due to improper handling and inefficient waste management practices (**He et al., 2018a; Karbalaei et al., 2018**). Likewise, plastic processing and recycling plants produce residues that are discharged into the environment and further transformed into MPs (**Karbalaei et al., 2018**). For example, larger quantities of raw materials utilized for manufacturing of plastics products were observed on the beaches closer to the plastic-processing and recycling plants (**Duis & Coors, 2016**).

Several groups of organisms such as earthworms can facilitate the conversion of primary MPs to secondary MPs and NPs by taking actions in their gizzard (**Rillig, 2012; Zhu et al., 2019**). Scraping or chewing mechanisms of Collembola or mites may lead to the generation of MPs and NPs from larger plastic debris. Likewise, burrowing mammals can also facilitate the incorporation of MPs in the soil via abrasion mechanism (**Rillig, 2012**). **Rillig et al. (2017)** reported that the activities of earthworms lead to the incorporation of PS into the soil profile from the top surface. There are various probable implications to the migration of MPs downward into deeper soil profile from the surface via existing organisms: (a) decomposition by the native microorganisms was very slow in the deeper part of the soil profile due to less microbial population (because of limited oxygen diffusion/availability), thus leading to more retention of MPs ; (b) entry of MPs in the soil

203 profile may also increase the chance of groundwater contamination with MPs and associated
204 chemicals; (c) conversion of MPs into NPs in the soil environment via disintegration,
205 decomposition, and abrasion may lead to further potential environmental menaces including
206 uptake of NPs by plants **(Rillig et al., 2017)**.

207

208 **3. Adverse effects of MPs in the soil environment**

209 Although MPs are defined as pure polymers of physical particles, they are often mixed with
210 other chemical entities such as heavy metals, dioxins, and polycyclic aromatic hydrocarbons
211 (**Hong et al., 2017**). Deliberate addition of extensive chemicals such flame retardants and
212 plasticizers to the plastic products, which subsequently become MPs, can cause hazards to soil
213 flora and fauna. A few studies demonstrated the possible pollutants transfer from MPs to beneficial
214 soil organisms such as earthworms while others indicated the role of MPs in causing toxicity to
215 the sludge digestive microbial flora or marine microbiota (**Gaylor et al., 2013**; **Oliviero et al.,**
216 **2019**; **Wei et al., 2019)**. During the manufacturing and processing of plastics, various chemicals
217 and additives are used to improve the properties and the applications of the final products **(Bolan**
218 **et al., 2020**) (**Table 3).** After longer exposure to the natural environment, these chemicals and
219 additives are leached into the soil environment via slow release/desorption and photochemical
220 degradation, causing adverse effects on soil microbial diversity and function (**Bolan et al., 2020;**
221 **Bolan & Bradney, 2019**). Therefore, the toxicity of these chemicals associated with MPs pollution
222 should be taken into account and carefully evaluated. A spectrum of pollutants such as pesticides
223 (**Nie et al., 2020**), dyes (**Kumar et al., 2019**), heavy metals (**Kumar et al., 2020**) were found in
224 the MPs-polluted environment. Large surface area of MPs enhances the adsorption of co-existing

225 pollutants, thus facilitating the transport and spreading of the laden contaminants that require
226 prudent consideration and future investigations (**Zhang et al., 2019**).

227 **3.1 Effects on plants**

228 There are two major questions to be addressed with plants and MPs: (a) whether plants can
229 accumulate MPs and (b) how absorbed MPs affect the plant growth and subsequently reach the
230 food chain (**Zhu et al., 2019**). It is difficult to distinguish the various types of MPs in a plant tissue,
231 which requires further studies and detailed investigations. There are different sizes of MPs
232 identified so far including the nanoscale and microscale ones, which can get across plant's
233 membranes and cell wall barriers and can be detected using fluorescent microbeads. **Bandmann**
234 **et al. (2012)** observed that endocytosis assisted the entry of nano-sized (less than 100 nm)
235 fluorescent PS beads inside a tobacco BY-2 cells, whereas edible plants were capable of
236 incorporating micro-sized (0.2 μm) fluorescent PS beads from the environment as indicated in the
237 whole plant culture study (**Li et al. 2019**). The pollution of MPs poses an additional risk to humans
238 via trophic food chain transfer. Only few recent studies reported the adverse effects of MPs on
239 plants (**Qi et al., 2018; Rillig et al., 2019).** For example, by spiking a soil sample with 1% PE
240 plastics and biodegradable particles in the soil, both types of MPs induced negative effects on
241 wheat plant and grain biomass, i.e., inhibition of the number and weight of the grain biomass.
242 Although earthworms used in the same study alleviated the influence of MPs to wheat, the study
243 did not include the examination of plant tissue containing PE particles.

244 **3.2 Effects on soil microorganisms**

245 Soil microorganisms, such as bacteria and fungi, can be affected by the exposure to
246 overwhelming quantity of MPs (**Bradney et al., 2019; Wijesekara et al., 2019**). The effects of

247 MPs on soil microorganisms were investigated, including their effects on bacterial transport,
248 spread of antibiotic resistant genes (ARGs), and overall microbial metabolisms. There was a
249 threshold for plastic particles to bring positive or negative impacts to the microbial activity. For
250 example, the addition of 0.05–0.4% polyester, 1 mg kg^{-1} PS, and 0.05–0.4% polyacrylic particles
251 stimulated negative impacts on the microbial activities (**Awet et al., 2018; de Souza Machado et**
252 **al., 2018a**), while 7% and 28% of PP particles led to positive impacts on the microbial activities
253 (**Liu et al., 2017)**. Many parameters including polymer shape, type, concentration, and size of the
254 MPs were variable in these studies, so it was difficult to generalize the toxic effects of MPs on the
255 microbial activities with respect to individual variables. Regarding the structure of microbial
256 community and soil structure, there was no direct evidence for deriving a generic conclusion on
257 the MPs toxicity based on these studies. More importantly, the high concentrations of MPs under
258 artificial spiking may be not representative of the field-relevant conditions.

259 The effects of MPs on microbial transport, metabolism, and genetic exchange are not
260 scrutinized but a few recent studies may provide some insights. **He et al. (2018b)** observed that
261 with increasing ionic strength, bacterial transport (*Escherichia coli*) in quartz sand was stimulated
262 by the PS particles, while no noticeable difference was reported under a low ionic strength where
263 both bacteria and PS particles displayed high mobility. The MPs were also found accountable for
264 the exchange of genes between phylogenetic non-related microorganisms as they introduced
265 additional exchange surface for genes and other metabolic products (**Huang et al., 2019; Sun et**
266 **al., 2018**). Along with the array of potentially beneficial genes, there were many harmful genes
267 such as ARGs that resulted in deleterious effects on human health upon transfer by MPs (**Arias-**
268 **Andres et al., 2018; Huang et al., 2019; Imran et al., 2019**). **Sun et al. (2018)** observed that the
269 retention times for ARGs and antibiotics were increased by the addition of 0.1% PS MPs to the

270 soil. More research should be conducted to provide additional and direct evidence on the ARGs
271 transmission by MPs.

272 **3.3 Effects on soil animals**

273 There are a few reports focusing on the effects of MPs on aquatic animals, but very limited data
274 are available for soil animals. A small subset of invertebrates was studied (including isopods,
275 nematodes, collembolan, and oligochaeta) to examine the effects of MPs on the growth, survival,
276 metabolism, gut microbiome, feeding pattern, and inflammatory reaction of soil animals (**Kim et**
277 **al., 2019; Lei et al., 2018**). **Lei et al. (2018)** experimented with 1 mg L^{-1} PS particles and exposed
278 a terrestrial nematode (*Caenorhabditis elegans*) to different sizes of PS particles (0.1, 0.5, 1.0, 2.0,
279 and 5.0 μm) for 72 h. The nematode with the 1.0 μm group demonstrated the shortest body length,
280 low survival rate, short lifespan, and even downregulation of unc-17 and unc-47 genes expression,
281 leading to irreversible damage of GABAergic and cholinergic neurons. These effects were
282 attributed to the immediate uptake and high accumulation of 1.0 μm particles by nematodes. The
283 concentration of MPs was considered as a significant variable affecting the organisms' activities.
284 **Zhu et al. (2018a)** conducted a concentration-dependent experiment with oligochaete *Enchytraeus*
285 *crypticus*. Small concentrations of PS (0.025 wt% in oatmeal) in soil showed a positive impact on
286 the weight of *Enchytraeus crypticus* while 0.5 wt% did not cause any significant changes. With 10
287 wt%, a negative shift was observed in the weight of gut microbiome. Similar findings were
288 validated by **Lwanga et al. (2016)**, who observed that the survival of *Lumbricus terrestris* was
289 adversely influenced by the addition of PE MPs in 28–60% litter (corresponding to 0.8–1.7 wt%
290 in soil), while PE MPs in 7% litter (0.2 wt% in soil) brought no significant change in the growth
291 and survival. Cytotoxicity analysis of MPs and biodegradable plastics on oligochaeta can be traced
292 through histological gut assessment. The addition of 0.0625–1 wt% PE MPs in soil did not cause

293 any deleterious effects on earthworm *Eisenia Andrei*, but induced immune response and tissue
294 damage under the exposure **(Rodriguez-Seijo et al., 2017)**. The starch-based biodegradable PE
295 films led to more negative effects on the growth of an earthworm in comparison to conventional
296 low-density PE. This might be because biodegradable plastics consisted of more toxic monomer
297 units, including polybutylene terephthalate (PBT) and polyethylene terephthalate (PET), than the
298 conventional PE plastics (**Rodriguez-Seijo et al., 2017)**.

299 A wide range of soil species is sensitive to MPs including collembolan strains such as *Folsomia*
300 *candida*. Experiments using $\delta^{15}N$ and $\delta^{13}C$ isotopes revealed that there was a substantial
301 modification in the metabolic turnover, i.e., 28.8% reproduction impairment and 16.8% growth
302 inhibition upon the addition of 0.1 wt% PVC MPs in soil (56-day exposure) **(Zhu et al., 2018b)**.
303 The impairment in reproduction and growth may be partly due to a shift in Collembolan
304 oviposition sites and feeding habits due to MPs (**Zhu et al., 2018b). Ju et al. (2019)** observed
305 similar results in the reproduction of *Folsomia* sp. when exposed to 0.1–1 wt% PE MPs in soil. In
306 both studies, modified animal gut microbiome was observed upon the exposure. These results
307 suggested that Collembolan species could be a potent indicator of MPs pollution and disturbance.
308 Owing to the significant role in litter decomposition, isopods are also employed as testing
309 organisms. Their energy reserve and feeding behavior were observed in the presence of 0.4 wt%
310 PE MPs with food pellets. Various end points were investigated including body mass index (BMI),
311 food assimilation, food ingestion, defecation rate, energy storage, and mortality. No effects were
312 observed after 14 days of exposure, indicating low deleterious effect of MPs to isopod *Porcellio*
313 *scaber* **(Kokalj et al., 2018).**

314 Recent research evaluated how MPs affected the bioaccumulation of organic pollutants, but
315 bioaccumulation tendency of MPs was still not much explored. Better understanding is required

316 regarding the transfer of MPs from one trophic level to another and the bioaccumulation tendency
317 of MPs in the soil environment. For instance, **Lwanga et al. (2017)** studied the increase in
318 concentration of MPs in home garden soil by analyzing earthworm casts and chicken feces. The
319 concentration of MPs increases throughout the trophic level with maximum concentration (129.8
320 ± 82.3 particles g^{-1}) in chicken feces with 10.2 ± 13.8 MPs particles per gizzard of the chicken.
321 This study predicted that the consumption of the chicken gizzard by humans can lead to the
322 accumulation of 840 plastic particles/person/year. The potential long-term effects of MPs on soil
323 organisms and soil animals should be further examined with future bioaccumulation and
324 biomagnification studies.

325

326 **4. Methods of extraction, detection, and characterization of MPs in agricultural systems**

327 The ubiquitous presence of MPs was studied in aquatic ecosystems (freshwater and marine)
328 using a variety of analytical methods (**Mai et al., 2018; Zhang et al., 2018a**). However, the
329 research maturity is still insufficient to develop the standardized methods for MPs quantification
330 in the soil and sediment ecosystems (**He et al., 2018a**). Soil is the uppermost layer of earth and
331 home to a wide array of organisms, where MPs get accumulated along with impurities and organic
332 matter. The soil composition plays an important role in the detection of MPs via floatation,
333 separation, and interference with infrared signaling (**von Sperber et al., 2017**). The development
334 of cost-effective, time-efficient, and accurate methods to analyze and quantify MPs in the
335 agricultural soils is an immediate need of the hour.

336 In order to assess the MPs pollution, proper selection of the sampling sites is required before
337 analysis and quantification can help us assess the actual status of the site. Collection of the MPs

samples is a crucial step in the analytical procedures. Different layers of top and bottom soil should be collected depending on the soil characteristics (**Liu et al., 2018; Zhou et al., 2018**). Then, density separation should be performed depending on the percentage of organic matter and clay on the dried, sieved, dispersed, filtered, and separated soil sample (**He et al., 2018a**). Density extraction and SOM digestion are carried out after which the extracted MPs can be visualized with an optical microscope. Raman and micro-Fourier transformed infrared (μ-FT-IR) spectroscopy are used for fingerprinting the types and distribution of MPs (**Liu et al., 2018; Peng et al., 2017**). The above protocol involving repetitive sieving and density separation is appropriate for analyzing the soil samples but requires future standardization of each procedure.

4.1 Extraction procedure

Variable sizes of sieves are used in consideration of the sample type and requirement. According to **NOAA (2015)** procedures, dry samples are initially sieved through a 5 mm size sieve, followed by stacked 5 mm and 0.3 mm sieves to segregate the disaggregated sediments as shown in **Figure 3**. Unlike sediment and water column samples, the soil samples are primarily segregated through a 2 mm size sieve after density separation of MPs (**Zhang & Liu, 2018**). MPs elements can be separated from the soil sample matrix using salt solutions with known concentrations as plastic particles float over high-density solution. The concentration of salt solution should be based on the density of the MPs as the concentration of 1.18 g cm^{-3} NaCl solutions is not enough to separate high-density plastics such as PVC and PET (**NOAA, 2015**).

A feasible and low-cost method for the extraction of light-density plastic particles including PP and PE from the soil was developed using distilled water with plastic recovery rates of almost 90% (**Zhang et al., 2018b**). The soil sample underwent heat treatment (3–5 s at 130 °C), which made the MPs present in the sample melt and converted into circular transparent particles that can

361 float on the water surface and be separated easily while other components, such as organic matter
362 and minerals, remain in their native form. **Liu et al. (2018)** used NaCl for MPs separation from
363 the agriculture soil sample with the ultrasonic treatment over prolonged floatation time. Seven out
364 of nine spiked MPs types were successfully extracted, including polymethyl methacrylate
365 (PMMA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyamide (PA), PE, PP,
366 and PS. The method was designed for PVC and PET but was found to be ineffective (**Liu et al.,**
367 **2018**). Different solutions were then proposed such as $CaCl_2$, which was efficient in the extraction
368 but led to agglomeration of organic matter and hindered the MPs identification (**Scheurer &**
369 **Bigalke, 2018**).

370 **Van Cauwenberghe et al. (2015)** suggested that the extraction solution would be efficient for
371 density range of 1.6–1.8 g cm^{-3}, which was attainable through the usage of NaI or $ZnCl_2$ along
372 with the addition of acid solution. However, these solutions are not environmentally friendly. Also,
373 acid solution can alter the characteristics of MPs in the soil samples. Other methods utilizing
374 oleophilic properties and electrostatic behavior of MPs were proposed. The oil extraction protocol
375 was efficient for achieving 90% recovery of MPs (**Crichton et al., 2017)**, while the electrostatic
376 behavior was 100% efficient in recovering plastics from multiple environmental matrices
377 including beach sand, water, and sediments (**Felsing et al., 2018**). However, their applicability for
378 a large-scale extraction of MPs from the soil samples is uncertain.

379 **4.2 Removal of SOM**

380 Density fractionization was not efficient enough to separate SOM from the soil samples
381 because they have a similar density (1.0 and 1.4 g cm^{-3}) to several plastics such as nylon and PET
382 (**Bläsing & Amelung, 2018**). Therefore, earlier studies utilized acids, alkalis, enzymatic digestion,
383 or oxidizing treatment (**Dehaut et al., 2016; Jabeen et a., 2017**). **Hurley et al. (2018)** tested the

384 effectiveness of different reagents, including 30% H_2O_2 solution, 10% KOH, 10 M NaOH, and
385 Fenton's reagent, of which Fenton's reagent in combination with density separation was found to
386 be the most suitable for SOM removal in the soil MPs assessment. However, these reagents were
387 likely to damage or modify the MPs. For instance, HNO_3 solution removed organic matter in a
388 short span but also damaged MPs of PET, PA, and ABS (**Dehaut et al., 2016; Rillig et al., 2017**),
389 while alkali treatment led to plastic abrasion (**Hurley et al., 2018).** Meanwhile, H_2O_2 would change
390 the structural morphology of PP and PE plastic but the change was minimal when it was used for
391 digestion at 70 °C. Therefore, H_2O_2 was considered as the most favorable oxidizing agent for the
392 removal of organic matter from the environment matrices (**He et al., 2018a; Hurley et al., 2018;**
393 **Jabeen et a., 2017; Zhang et al., 2018b**). **Liu et al. (2018)** confirmed that the oxidation by H_2O_2
394 was efficient for SOM removal from the agricultural soils.

395 **4. 3 Identification and characterization**

396 Subsequent to the isolation of MPs from environmental samples, several techniques are
397 applied for the identification, quantification, and characterization of MPs as listed in **Table 4**. The
398 samples are first visually identified for their surface texture after the classification based on their
399 shape, size, and color (**He et al., 2018a**). Chemical classification is performed using gas
400 chromatography mass spectroscopy, Raman, or infrared spectroscopy (**Li et al., 2018**). MPs are
401 sorted and grouped according to their sizes. In addition, MPs are sorted in terms of their shapes,
402 namely fragment, fiber, foam, bead, and film. Although visual identification is a feasible step to
403 start classifying an enormous variety of MPs, it possesses its own limitations with human errors.
404 **Eriksen et al. (2013)** reported 20% of aluminum silicate particles being visually misinterpreted as
405 MPs through a confirmation by SEM. **Lenz et al. (2015) reported that** nearly 70% of the particles
406 were erroneously labeled as MPs using FTIR and 32% of visually labelled MPs were not identified

407 by μ-Raman spectroscopy. There was a need for combining visual identification with other
408 confirmatory physical and chemical techniques in the classification of MPs. SEM provides high
409 magnification image of the sample but requires longer time and higher costs (sample preparation,
410 coating, analytical cost). The sample coatings may disturb the surface texture and result in
411 inaccuracies in the detection of MPs (**Bläsing & Amelung, 2018; Shim et al., 2017; Zhoa et al.,**
412 **2018**).

413 One of the most popular non-destructive chemical techniques to identify MPs is infrared
414 microscopy along with μ-Raman, attenuated total reflectance (ATR), and μ-FT-IR spectroscopy,
415 which offer an advantage of microspectrometry coupled with automated scanning (**Bläsing &**
416 **Amelung, 2018**). μ-Raman is more sensitive than μ-FTIR as it can detect MPs size as small as 1
417 μm while μ-FTIR is effective for particles size >10-20 μm (**Cai et al., 2017**). The presence of
418 organic matter interferes with the signaling, which can be avoided using a fluorescent background
419 in the case of Raman spectroscopy **(Silva et al., 2018; von Sperber et al., 2017**). Both techniques
420 are time-consuming and costly but provide reliable information on MPs. There are a few
421 alternative techniques available such as hyperspectral imaging which can visualize 0.5 to 5 μm
422 particles on the soil surface, and macroscopic dimensioned near-infrared spectroscopy combined
423 with chemometrics which is rapid and does not require any chemical pretreatment (**Paul et al.,**
424 **2019**; **Shan et al., 2018**). Another technique of thermal extraction desorption-gas chromatography-
425 mass spectrometry (TED-GC-MS) can achieve accurate and specific quantification of PP, PE, PS,
426 and PET (**Dümichen et al., 2017**).

427 Many parameters remain largely variable even after classifications by means of environmental
428 factors, temporal and spatial variability patterns, reporting units, etc. It is difficult to characterize
429 MPs in the organic matter-rich agricultural soils, and there are disparities to compare the data and

430 generate reproducible results owing to the use of different techniques. Therefore, standardization
431 of methodological protocols is essential for effective comparison and monitoring.
432

433 **5. Challenges and future directions**

434 The pollution of MPs is worsening globally and the related hazards in agricultural soils need
435 proper attention. This review describes the analytical techniques, ecological risks, and pollution
436 characteristics of MPs in the soil environment. Scientific knowledge of MPs encompassing the
437 sources, fate, environmental concentrations, analytical techniques, and ecological consequence are
438 reviewed. There are noticeable knowledge gaps that demand more concerted efforts in future
439 research, and the following challenges are of high priority:

440 • There is no standard protocol to isolate, quantify and characterize MPs from soil
441 environment. It is vital to develop a precise, feasible, and efficient assay for multiple MPs
442 identification and characterization. Future research should focus on devising a testing
443 protocol that takes into account the variable environmental soil conditions and the
444 heterogeneity of MPs. Depending on the origin, shape, size, and composition of MPs, it is
445 necessary to standardize specific methods for sample collection, isolation, identification,
446 and analysis of MPs in the organic matter-rich agricultural soils.
447 • There is only a limited size of database concerning the sources and fate of MPs in the soil
448 environment and their interactions with microbes, food crops, and soil animals. We need
449 to evaluate the distribution, transport, and degradation of MPs to holistically reveal their
450 environmental effects and implications in the agricultural field. With time MPs are
451 degraded partially by a range of physicochemical and microbiological drivers. It is crucial

452 to identify the individual roles of relevant natural and anthropogenic activities to elucidate
453 the long-term fate of MPs in the soil ecosystem.

454 • Currently, the global and regional data inventory (types, concentration, composition, and
455 types of MPs) for the pollution status of MPs in the agricultural systems and soil
456 environment are very limited and require substantial expansion. Future research should be
457 extended to the qualitative characterization and quantitative assessment of the MPs in
458 different types of agricultural soils with different cropping systems under variable
459 climates, as well as their interactions and transformations in the rhizosphere.

460 • MPs are recognized as emerging persistent pollutants that may transfer across different
461 trophic levels along a food web. It is crucial to determine its potential cytotoxic effects on
462 soil flora and animals/humans and evaluate the apparent transgenerational effects. It is also
463 necessary to investigate both natural and engineered ecosystems to study the behavioral
464 responses of plants, animals, and other microbial assemblages to widespread MPs pollution
465 in the agricultural soils.

466 • MPs as vectors of a broad range of environmental pollutants may facilitate or inhibit the
467 mobility and bioavailability of these environmentally persistent and potentially hazardous
468 pollutants in the agricultural soils. Although this area has been extensively examined in the
469 aquatic ecosystems, limited knowledge is available for different terrestrial ecosystems and
470 needs to be properly addressed by future research studies.

471 • With the increasing recognition of the hazardous effects of MPs, behavioral change of
472 consumers and plastics manufacturers would be necessary for attaining sustainable plastic
473 waste management. Well-aligned initiatives, best management practices, more stringent
474 policies, and joint efforts of citizens and government officials are urgently needed to reduce

illegal disposal of plastic wastes and improper use of plastic products in the agricultural industry for the sake of food safety and sustainable development.

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References

Alvarenga, P., Farto, M., Mourinha, C., Palma, P., 2016. Beneficial use of dewatered and composted sewage sludge as soil amendments: behaviour of metals in soils and their uptake by plants. Waste Biomass Valorization. 7(5), 1189-1201. DOI 10.1007/s12649-016-9519-z.

Arias-Andres, M., Klümper, U., Rojas-Jimenez, K., Grossart, H. P., 2018. Microplastic pollution increases gene exchange in aquatic ecosystems. Environ Pollut. 237, 253-261. https://doi.org/10.1016/j.envpol.2018.02.058.

Arkatkar, A., Arutchelvi, J., Bhaduri, S., Uppara, P. V., Doble, M., 2009. Degradation of unpretreated and thermally pretreated polypropylene by soil consortia. Int Biodeterior Biodegradation. 63(1), 106-111. https://doi.org/10.1016/j.ibiod.2008.06.005.

Awet, T. T., Kohl, Y., Meier, F., Straskraba, S., Grün, A. L., Ruf, T., Jost, C., Drexel, R., Tunc, E., Emmerling, C., 2018. Effects of polystyrene nanoparticles on the microbiota and

497 functional diversity of enzymes in soil. Environ. Sci. Eur., 30(1), 1-10.
498 https://doi.org/10.1186/s12302-018-0140-6.
499 Bandmann, V., Müller, J. D., Köhler, T., Homann, U., 2012. Uptake of fluorescent nano beads
500 into BY2-cells involves clathrin-dependent and clathrin-independent endocytosis. FEBS
501 letters. 586(20), 3626-3632. **https://doi.org/10.1016/j.febslet.2012.08.008**.
502 Bhunia, K., Sablani, S. S., Tang, J., Rasco, B., 2013. Migration of chemical compounds from
503 packaging polymers during microwave, conventional heat treatment, and storage. COMPR
504 REV FOOD SCI F. 12(5), 523-545. https://doi.org/10.1111/1541-4337.12028.
505 Biron, M., 2003. Thermosets and composites. *Elsevier*. ISBN: 9780080519203.
506 Bittner, G. D., Denison, M. S., Yang, C. Z., Stoner, M. A., He, G., 2014. Chemicals having
507 estrogenic activity can be released from some bisphenol a-free, hard and clear, thermoplastic
508 resins. Environ. Health. 13(1), 103. http://www.ehjournal.net/content/13/1/103.
509 Bläsing, M., Amelung, W., 2018. Plastics in soil: Analytical methods and possible sources. Sci
510 Total Environ. 612, 422-435. https://doi.org/10.1016/j.scitotenv.2017.08.086.
511 Bolan, N., Bradney, L., 2019. Particulate plastics in soils. Chemistry in Australia, (Jul/Aug 2019),
512 18.
513 Bolan, N., Kirkham, M. B., Halsband, C., Nugegoda, D, Ok, Y. S., 2020. Particulate Plastics in
514 Terrestrial and Aquatic Environments. CRC Press. ISBN 9780367511401.
515 Boots, B., Russell, C. W., Green, D. S., 2019. Effects of Microplastics in Soil Ecosystems: Above
516 and Below Ground. Environ. Sci. Technol. 53(19), 11496-11506.
517 https://doi.org/10.1021/acs.est.9b03304.
518 Bradney, L., Wijesekara, H., Palansooriya, K.N., Obadamudalige, N., Bolan, N.S., Ok, Y.S.,
519 Rinklebe, J., Kim, K.H., Kirkham, M.B., 2019. Particulate plastics as a vector for toxic trace-

element uptake by aquatic and terrestrial organisms and human health risk. Environ. Int. 131, 104937. https://doi.org/10.1016/j.envint.2019.104937.

Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., Chen, Q., 2017. Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environ. Sci. Pollut. 24(32), 24928-24935. DOI 10.1007/s11356-017-0116-x.

César, M. E. F., Mariani, P. D. S. C., Innocentini-Mei, L. H., Cardoso, E. J. B. N., 2009. Particle size and concentration of poly (ε-caprolactone) and adipate modified starch blend on mineralization in soils with differing textures. Polym. Test. 28(7), 680-687. https://doi.org/10.1016/j.polymertesting.2009.05.002.

Chae, Y., An, Y. J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. Environ. Pollut. 240, 387-395. https://doi.org/10.1016/j.envpol.2018.05.008.

Crichton, E. M., Noël, M., Gies, E. A., Ross, P. S., 2017. A novel, density-independent and FTIR-compatible approach for the rapid extraction of microplastics from aquatic sediments. Anal. Methods. 9(9), 1419-1428. https://doi.org/10.1039/C6AY02733D.

de Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M. C., 2018a. Microplastics as an emerging threat to terrestrial ecosystems. Glob. Change Biol. 24(4), 1405-1416. https://doi.org/10.1111/gcb.14020.

de Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., Becker, R., Görlich, A.S., Rillig, M. C., 2019. Microplastics can change soil properties and affect plant performance. Environ. Sci. Technol. 53(10), 6044-6052. https://doi.org/10.1021/acs.est.9b01339.

542 de Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., Rillig, M.
543 C.,2018b. Impacts of microplastics on the soil biophysical environment. Environ. Sci.
544 Technol. 52(17), 9656-9665. https://doi.org/10.1021/acs.est.8b02212.
545 Dehaut, A., Cassone, A. L., Frère, L., Hermabessiere, L., Himber, C., Rinnert, E., Rivière, G.,
546 Lambert, C., Soudant, P., Huvet, A., Duflos, G., 2016. Microplastics in seafood: Benchmark
547 protocol for their extraction and characterization. Environ. Pollut. 215, 223-233.
548 https://doi.org/10.1016/j.envpol.2016.05.018.
549 Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with
550 a specific focus on personal care products), fate and effects. Environ. Sci. Eur. 28(1), 2. DOI
551 10.1186/s12302-015-0069-y.
552 Dümichen, E., Eisentraut, P., Bannick, C. G., Barthel, A. K., Senz, R., Braun, U., 2017. Fast
553 identification of microplastics in complex environmental samples by a thermal degradation
554 method. Chemosphere. 174, 572-584. https://doi.org/10.1016/j.chemosphere.2017.02.010.
555 Elert, A. M., Becker, R., Duemichen, E., Eisentraut, P., Falkenhagen, J., Sturm, H., Braun, U.,
556 2017. Comparison of different methods for MP detection: what can we learn from them, and
557 why asking the right question before measurements matters? Environ. Pollut. 231, 1256-1264.
558 https://doi.org/10.1016/j.envpol.2017.08.074.
559 Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H., Amato, S., 2013.
560 Microplastic pollution in the surface waters of the Laurentian Great Lakes. Mar Pollut Bull.
561 77(1-2), 177-182. https://doi.org/10.1016/j.marpolbul.2013.10.007.
562 Felsing, S., Kochleus, C., Buchinger, S., Brennholt, N., Stock, F., Reifferscheid, G., 2018. A new
563 approach in separating microplastics from environmental samples based on their electrostatic
564 behavior. Environ. Pollut. 234, 20-28. https://doi.org/10.1016/j.envpol.2017.11.013.

565 Fuller, S., Gautam, A., 2016. A procedure for measuring microplastics using pressurized fluid
566 extraction. Environ. Sci. Technol. 50(11), 5774-5780.
567 https://doi.org/10.1021/acs.est.6b00816.
568 Gächter, R., Müller, H., Klemchuck, P. P., 1993. Stabilizers, Processing Aids, Plasticizers, Fillers,
569 Reinforcements, Colorants for Thermoplastics. Plastics Additives Handbook—4th Edition,
570 Carl Hanser Verlag, Munich, Vienna, New York, Barcelona.
571 Galloway, T. S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the
572 marine ecosystem. Nat. Ecol. Evol. 1(5), 1-8. https://doi.org/10.1038/s41559-017-0116.
573 Gaylor, M. O., Harvey, E., Hale, R. C., 2013. Polybrominated diphenyl ether (PBDE)
574 accumulation by earthworms (Eisenia fetida) exposed to biosolids-, polyurethane foam
575 microparticle-, and penta-BDE-amended soils. Environ. Sci. Technol. 47(23), 13831-13839.
576 https://doi.org/10.1021/es403750a.
577 Geyer, R., Jambeck, J. R., Law, K. L., 2017. Production, use, and fate of all plastics ever made. Sci.
578 Adv. 3(7), e1700782. DOI: 10.1126/sciadv.1700782.
579 Gies, E. A., LeNoble, J. L., Noël, M., Etemadifar, A., Bishay, F., Hall, E. R., Ross, P. S., 2018.
580 Retention of microplastics in a major secondary wastewater treatment plant in Vancouver,
581 Canada. Mar. Pollut. 133, 553-561. https://doi.org/10.1016/j.marpolbul.2018.06.006.
582 Guo, J.J., Huang, X.P., Xiang, L., Wang, Y.Z., Li, Y.W., Li, H., Cai, Q.Y., Mo, C.H., Wong, M.H.,
583 2020. Source, migration and toxicology of microplastics in soil. Environ. Int. 137, 105263.
584 https://doi.org/10.1016/j.envint.2019.105263.
585 Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of
586 chemical additives present in plastics: migration, release, fate and environmental impact

587 during their use, disposal and recycling. J. Hazard. Mater. 344, 179-199.
588 https://doi.org/10.1016/j.jhazmat.2017.10.014.
589 Hansen, E., Nilsson, N., Vium, K. S. R., 2013. Hazardous Substances in PlasticMaterials, COWI
590 in cooperation with Danish Technological Institute. http://www.byggemiljo.no/wp-
591 content/uploads/2014/10/72_ta3017.pdf.
592 He, D., Luo, Y., Lu, S., Liu, M., Song, Y., Lei, L., 2018a. Microplastics in soils: analytical
593 methods, pollution characteristics and ecological risks. Trends Anal. Chem, 109, 163-172.
594 https://doi.org/10.1016/j.trac.2018.10.006.
595 He, L., Wu, D., Rong, H., Li, M., Tong, M., Kim, H., 2018b. Influence of nano-and microplastic
596 particles on the transport and deposition behaviors of bacteria in quartz sand. Environ. Sci.
597 Technol. 52(20), 11555-11563. https://doi.org/10.1021/acs.est.8b01673.
598 Hintersteiner, I., Himmelsbach, M., Buchberger, W. W., 2015. Characterization and quantitation
599 of polyolefin microplastics in personal-care products using high-temperature gel-permeation
600 chromatography. Anal. Bioanal. Chem. 407(4), 1253-1259. https://doi.org/10.1007/s00216-
601 014-8318-2.
602 Hong, S. H., Shim, W. J., Hong, L., 2017. Methods of analysing chemicals associated with
603 microplastics: a review. Anal. Methods. 9(9), 1361-1368.
604 https://doi.org/10.1039/C6AY02971J.
605 Horton, A. A., Svendsen, C., Williams, R. J., Spurgeon, D. J., Lahive, E., 2017a. Large
606 microplastic particles in sediments of tributaries of the River Thames, UK–Abundance,
607 sources and methods for effective quantification. Mar Pollut Bull. 114(1), 218-226.
608 https://doi.org/10.1016/j.marpolbul.2016.09.004.

609 Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., Svendsen, C., 2017b. Microplastics in
610 freshwater and terrestrial environments: evaluating the current understanding to identify the
611 knowledge gaps and future research priorities. Sci Total Environ. 586, 127-141.
612 https://doi.org/10.1016/j.scitotenv.2017.01.190.
613 Huang, F. Y., Yang, K., Zhang, Z. X., Su, J. Q., Zhu, Y. G., Zhang, X., 2019. Effects of
614 microplastics on antibiotic resistance genes in estuarine sediments. Huan jing ke xue=
615 Huanjing kexue, 40(5), 2234-2239. http://kns.cnki.net/kcms/detai l/11.1895.X.20181
616 219.1755.027.htm.
617 Huang, Y., Liu, Q., Jia, W., Yan, C., Wang, J., 2020. Agricultural plastic mulching as a source of
618 microplastics in the terrestrial environment. Environ. Pollut. 260, 114096.
619 https://doi.org/10.1016/j.envpol.2020.114096.
620 Hurley, R. R., Lusher, A. L., Olsen, M., Nizzetto, L., 2018. Validation of a method for extracting
621 microplastics from complex, organic-rich, environmental matrices. Environ. Sci. Technol.
622 52(13), 7409-7417. https://doi.org/10.1021/acs.est.8b01517.
623 Imran, M., Das, K. R., Naik, M. M., 2019. Co-selection of multi-antibiotic resistance in bacterial
624 pathogens in metal and microplastic contaminated environments: An emerging health
625 threat. Chemosphere. 215, 846-857. https://doi.org/10.1016/j.chemosphere.2018.10.114.
626 Ivleva, N. P., Wiesheu, A. C., Niessner, R., 2017. Microplastic in aquatic ecosystems. Angew.
627 Chem. Int. Ed. 56(7), 1720-1739. https://doi.org/10.1002/anie.201606957.
628 Jabeen, K., Su, L., Li, J., Yang, D., Tong, C., Mu, J., Shi, H., 2017. Microplastics and mesoplastics
629 in fish from coastal and fresh waters of China. Environ. Pollut. 221, 141-149.
630 https://doi.org/10.1016/j.envpol.2016.11.055.

631 Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law,
632 K.L., 2015. Plastic waste inputs from land into the ocean. Science. 347(6223), 768-771.
633 Ju, H., Zhu, D., Qiao, M., 2019. Effects of polyethylene microplastics on the gut microbial
634 community, reproduction and avoidance behaviors of the soil springtail, Folsomia
635 candida. Environ. Pollut. 247, 890-897. https://doi.org/10.1016/j.envpol.2019.01.097.
636 Karbalaei, S., Hanachi, P., Walker, T. R., Cole, M., 2018. Occurrence, sources, human health
637 impacts and mitigation of microplastic pollution. Environ Sci Pollut Res. 25(36), 36046-
638 36063. https://doi.org/10.1007/s11356-018-3508-7.
639 Kim, H. M., Lee, D. K., Long, N. P., Kwon, S. W., Park, J. H., 2019. Uptake of nanopolystyrene
640 particles induces distinct metabolic profiles and toxic effects in Caenorhabditis
641 elegans. Environ. Pollut. 246, 578-586. https://doi.org/10.1016/j.envpol.2018.12.043.
642 Kokalj, A. J., Horvat, P., Skalar, T., Kržan, A., 2018. Plastic bag and facial cleanser derived
643 microplastic do not affect feeding behaviour and energy reserves of terrestrial isopods. Sci
644 Total Environ. 615, 761-766. https://doi.org/10.1016/j.scitotenv.2017.10.020.
645 Kole, P. J., Löhr, A. J., Van Belleghem, F. G., Ragas, A. M., 2017. Wear and tear of tyres: a
646 stealthy source of microplastics in the environment. Int. J. Environ. Res. Public
647 Health. 14(10), 1265. https://doi.org/10.3390/ijerph14101265.
648 Kumar, M., Kumar, M., Pandey, A., Thakur, I. S., 2019. Genomic analysis of carbon dioxide
649 sequestering bacterium for exopolysaccharides production. Sci. Rep. 9(1), 1-12.
650 https://doi.org/10.1038/s41598-019-41052-0.
651 Kumar, M., Sun, Y., Rathour, R., Pandey, A., Thakur, I. S., Tsang, D. C., 2020. Algae as potential
652 feedstock for the production of biofuels and value-added products: Opportunities and
653 challenges. Sci Total Environ. 137116. https://doi.org/10.1016/j.scitotenv.2020.137116.

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., Glas, M., Schludermann, E., 2014. The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environ. Pollut. 188, 177-181. https://doi.org/10.1016/j.envpol.2014.02.006.

Lei, L., Liu, M., Song, Y., Lu, S., Hu, J., Cao, C., Xie B, Shi H., He, D., 2018. Polystyrene (nano) microplastics cause size-dependent neurotoxicity, oxidative damage and other adverse effects in Caenorhabditis elegans. Environ. Sci. Nano, 5(8), 2009-2020. https://doi.org/10.1039/C8EN00412A.

Lenz, R., Enders, K., Stedmon, C. A., Mackenzie, D. M., Nielsen, T. G., 2015. A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Mar Pollut Bull. 100(1), 82-91. https://doi.org/10.1016/j.marpolbul.2015.09.026.

Li, J., Liu, H., Chen, J. P., 2018. Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Res. 137, 362-374. https://doi.org/10.1016/j.watres.2017.12.056.

Li, J., Song, Y., Cai, Y., 2020. Focus topics on microplastics in soil: Analytical methods, occurrence, transport, and ecological risks. Environ Pollut. 257, 113570. https://doi.org/10.1016/j.envpol.2019.113570.

Li, L., Zhou, Q., Yin, N., Tu, C., Luo, Y., 2019. Uptake and accumulation of microplastics in an edible plant. Chin Sci Bull. 64(9), 928-934. https://doi.org/10.1360/N972018-00845.

Liu, H., Yang, X., Liu, G., Liang, C., Xue, S., Chen, H., Ritsema, C. J., Geissen, V., 2017. Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. Chemosphere. 185, 907-917. https://doi.org/10.1016/j.chemosphere.2017.07.064.

677 Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X. He, D.,
678 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai,
679 China. Environ. Pollut. 242, 855-862. https://doi.org/10.1016/j.envpol.2018.07.051.
680 Löhr, A. J., Belleghem, F. G. A. J., Ragas, A. M. J., 2017. Wear and tear of tyres: A stealthy source
681 of microplastics in the environment. Int. J. Environ. Res. Public Health 14, 1265.
682 doi:10.3390/ijerph14101265.
683 Lv, W., Zhou, W., Lu, S., Huang, W., Yuan, Q., Tian, M., Lv, W., He, D., 2019. Microplastic
684 pollution in rice-fish co-culture system: A report of three farmland stations in Shanghai,
685 China. Sci Total Environ. 652, 1209-1218. https://doi.org/10.1016/j.scitotenv.2018.10.321.
686 Lwanga, H.E., Gertsen, H., Gooren, H., Peters, P., Salánki, T., van der Ploeg, M., Besseling E,
687 Koelmans, A. A., Geissen, V., 2016. Microplastics in the terrestrial ecosystem: implications
688 for Lumbricus terrestris (Oligochaeta, Lumbricidae). Environ. Sci. Technol. 50(5), 2685-
689 2691. https://doi.org/10.1021/acs.est.5b05478.
690 Mai, L., Bao, L. J., Shi, L., Wong, C. S., Zeng, E. Y., 2018. A review of methods for measuring
691 microplastics in aquatic environments. Environ Sci Pollut Res. 25(12), 11319-11332.
692 https://doi.org/10.1007/s11356-018-1692-0.
693 Mintenig, S. M., Int-Veen, I., Löder, M. G., Primpke, S., Gerdts, G., 2017. Identification of
694 microplastic in effluents of waste water treatment plants using focal plane array-based micro-
695 Fourier-transform infrared imaging. Water Res. 108, 365-372.
696 https://doi.org/10.1016/j.watres.2016.11.015.
697 Nie, J., Sun, Y., Zhou, Y., Kumar, M., Usman, M., Li, J., Shao, J., Wang, L., Tsang, D. C., 2020.
698 Bioremediation of water containing pesticides by microalgae: Mechanisms, methods, and

prospects for future research. Sci Total Environ. 707, 136080. https://doi.org/10.1016/j.scitotenv.2019.136080.

Nizzetto, L., Futter, M., Langaas, S., 2016a. Are agricultural soils dumps for microplastics of urban origin?. Environ. Sci. Technol 50, 10777–10779. https://doi.org/10.1021/acs.est.6b04140.

Nizzetto, L., Langaas, S., Futter, M. (2016b). Pollution: Do microplastics spill on to farm soils?. Nature. 537(7621), 488-488. https://doi.org/10.1038/537488b.

NOAA, Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments, 2015. https://marinedebris.noaa.gov/sites/default/files/publications files/noaa_microplastics_methods_manual.pdf. (Accessed 15 November 2015).

Oliviero, M., Tato, T., Schiavo, S., Fernández, V., Manzo, S., Beiras, R., 2019. Leachates of micronized plastic toys provoke embryotoxic effects upon sea urchin Paracentrotus lividus. Environ. Pollut. 247, 706-715. https://doi.org/10.1016/j.envpol.2019.01.098.

Paul, A., Wander, L., Becker, R., Goedecke, C., Braun, U., 2019. High-throughput NIR spectroscopic (NIRS) detection of microplastics in soil. Environ Sci Pollut Res. 26(8), 7364-7374. https://doi.org/10.1007/s11356-018-2180-2.

Peng, J., Wang, J., Cai, L., 2017. Current understanding of microplastics in the environment: occurrence, fate, risks, and what we should do. ntegr. Environ. Assess. Manag. 13(3), 476-482. https://doi.org/10.1002/ieam.1912.

Plasticseurope (2015). Plastics — The Facts 2014/2015. https://www.plasticseurope.org/application/files/5515/1689/9220/2014plastics_the_facts_PubFeb2015.pdf.

721 Plasticseurope(2018).https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_t
722 he_facts_2018_AF_web.pdf.
723 Prata, J. C., 2018. Airborne microplastics: consequences to human health?. Environ. Pollut. 234,
724 115-126. https://doi.org/10.1016/j.envpol.2017.11.043.
725 Qi, R., Jones, D.L., Li, Z., Liu, Q., Yan, C., 2020. Behavior of microplastics and plastic film
726 residues in the soil environment: A critical review. Sci. Total Environ. 703, 134722.
727 https://doi.org/10.1016/j.scitotenv.2019.134722.
728 Qi, Y., Yang, X., Pelaez, A. M., Lwanga, E. H., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V.,
729 2018. Macro-and micro-plastics in soil-plant system: effects of plastic mulch film residues
730 on wheat (Triticum aestivum) growth. Sci Total Environ. 645, 1048-1056.
731 https://doi.org/10.1016/j.scitotenv.2018.07.229.
732 Ramos, L., Berenstein, G., Hughes, E. A., Zalts, A., Montserrat, J. M., 2015. Polyethylene film
733 incorporation into the horticultural soil of small periurban production units in Argentina. Sci
734 Total Environ. 523, 74-81. https://doi.org/10.1016/j.scitotenv.2015.03.142.
735 Rehse, S., Kloas, W., Zarfl, C., 2016. Short-term exposure with high concentrations of pristine
736 microplastic particles leads to immobilisation of Daphnia magna. Chemosphere. 153, 91-99.
737 https://doi.org/10.1016/j.chemosphere.2016.02.133.
738 Rillig, M. C., 2012. Microplastic in terrestrial ecosystems and the soil?. Environ. Sci. Technol.
739 46,6453–6454. dx.doi.org/10.1021/es302011r.
740 Rillig, M. C., Lehmann, A., de Souza Machado, A. A., Yang, G., 2019. Microplastic effects on
741 plants. New Phytol. 223(3), 1066-1070. https://doi.org/10.1111/nph.15794.
742 Rillig, M. C., Ziersch, L., Hempel, S., 2017. Microplastic transport in soil by earthworms. Sci.
743 Rep. 7. https://doi.org/10.1038/s41598-017-01594-7.

Rillig, M.C., Ingraffia, R., de Souza Machado, A.A., 2017. Microplastic incorporation into soil in agroecosystems. Frontiers in plant science. 8, 1805. doi: 10.3389/fpls.2017.01805.

Rodriguez-Seijo, A., Lourenço, J., Rocha-Santos, T. A. P., Da Costa, J., Duarte, A. C., Vala, H., Pereira, R., 2017. Histopathological and molecular effects of microplastics in Eisenia andrei Bouché. Environ. Pollut. 220, 495-503. https://doi.org/10.1016/j.envpol.2016.09.092.

Sablani, S. S., Rahman, M. S., 2007. Food packaging interaction. In Handbook of food preservation (pp. 957-974). CRC Press.

Scheurer, M., Bigalke, M., 2018. Microplastics in Swiss floodplain soils. Environ. Sci. Technol. 52(6), 3591-3598. https://doi.org/10.1021/acs.est.7b06003.

Shim, W. J., Hong, S. H., Eo, S. E., 2017. Identification methods in microplastic analysis: a review. Anal. Methods. 9(9), 1384-1391. https://doi.org/10.1039/C6AY02558G.

Shim, W. J., Song, Y. K., Hong, S. H., Jang, M., 2016. Identification and quantification of microplastics using Nile Red staining. Mar Pollut Bull. 113(1-2), 469-476. https://doi.org/10.1016/j.marpolbul.2016.10.049.

Silva, A. B., Bastos, A. S., Justino, C. I., da Costa, J. P., Duarte, A. C., Rocha-Santos, T. A., 2018. Microplastics in the environment: Challenges in analytical chemistry-A review. Anal. Chim. Acta. 1017, 1-19. https://doi.org/10.1016/j.aca.2018.02.043.

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñoz, K., Frör, O., Schaumann, G. E., 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation?. Sci Total Environ. 550, 690-705. https://doi.org/10.1016/j.scitotenv.2016.01.153.

Strråt, M., Nilsson, C., 2018. Decabromodiphenyl ether and other flame retardants in plastic waste destined for recycling. Swerea IFM, Project report, M-973.

Sun, M., Ye, M., Jiao, W., Feng, Y., Yu, P., Liu, M., Jiao, J., He, X., Liu, K., Wu, J., 2018. Changes in tetracycline partitioning and bacteria/phage-comediated ARGs in microplastic-contaminated greenhouse soil facilitated by sophorolipid. J. Hazard. Mater. 345, 131-139. https://doi.org/10.1016/j.jhazmat.2017.11.036.

United Nations Environment Programme (UNEP, 2016): Marine Plastic Debris and Microplastics — Global Lessons and Research to Inspire Action and Guide Policy Change. Nairobi.

Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbens, J., Janssen, C. R., 2015. Microplastics in sediments: a review of techniques, occurrence and effects. Mar. Environ. Res. 111, 5-17. https://doi.org/10.1016/j.marenvres.2015.06.007.

von Sperber, C., Lewandowski, H., Tamburini, F., Bernasconi, S. M., Amelung, W., Frossard, E., 2017. Kinetics of enzyme-catalysed oxygen isotope exchange between phosphate and water revealed by Raman spectroscopy. J. Raman Spectrosc. 48(3), 368-373. https://doi.org/10.1002/jrs.5053.

Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G., Zhang, P., 2019. Microplastics as contaminants in the soil environment: A mini-review. Sci Total Environ. 691, 848-857. https://doi.org/10.1016/j.scitotenv.2019.07.209.

Wei, W., Huang, Q. S., Sun, J., Wang, J. Y., Wu, S. L., Ni, B. J., 2019. Polyvinyl chloride microplastics affect methane production from the anaerobic digestion of waste activated sludge through leaching toxic bisphenol-A. Environ. Sci. Technol. 53(5), 2509-2517. https://doi.org/10.1021/acs.est.8b07069.

Weithmann, N., Möller, J. N., Löder, M. G., Piehl, S., Laforsch, C., Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci. Adv. 4(4), eaap8060. DOI: 10.1126/sciadv.aap8060.

Whitacre, D. M., 2014. Reviews of environmental contamination and toxicology. New York, NY: Springer, 227. https://doi.org/10.1007/ 978-3-319-03777-6.

Wijesekara, H., Bolan, N. S., Bradney, L., Obadamudalige, N., Seshadri, B., Kunhikrishnan, A., Dharmarajan, R., Ok, Y. S., Rinklebe, J., Kirkham, M.B., Vithanage, M., 2018. Trace element dynamics of biosolids-derived microbeads. Chemosphere. 199, 331-339. https://doi.org/10.1016/j.chemosphere.2018.01.166.

Zhan, Z. W., Wang, J. D., Peng, J. P., Xie, Q. L., Huang, Y., Gao, Y. F., 2016. Sorption of 3,30,4,40-tetrachlorobiphenyl by microplastics: A case study of polypropylene. Mar Pollut Bull. 110, 559–563. https://doi.org/10.1016/j.marpolbul.2016.05.036.

Zhang, G. S., Liu, Y. F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Sci Total Environ. 642, 12-20. https://doi.org/10.1016/j.scitotenv.2018.06.004.

Zhang, K., Shi, H., Peng, J., Wang, Y., Xiong, X., Wu, C., Lam, P. K., 2018a. Microplastic pollution in China's inland water systems: A review of findings, methods, characteristics, effects, and management. Sci Total Environ. 630, 1641-1653. https://doi.org/10.1016/j.scitotenv.2018.02.300.

Zhang, S., Wang, J., Liu, X., Qu, F., Wang, X., Wang, X., Li, Y., Sun, Y., 2019. Microplastics in the environment: A review of analytical methods, distribution, and biological effects. Trends Analyt Chem. 111, 62-72. https://doi.org/10.1016/j.trac.2018.12.002.

Zhang, S., Yang, X., Gertsen, H., Peters, P., Salánki, T., Geissen, V., 2018b. A simple method for the extraction and identification of light density microplastics from soil. Sci Total Environ. 616, 1056-1065. https://doi.org/10.1016/j.scitotenv.2017.10.213

Zhao, J., Liu, L., Zhang, Y., Wang, X., Wu, F., 2018. A novel way to rapidly monitor microplastics in soil by hyperspectral imaging technology and chemometrics. Environ. Pollut. 238, 121-129. https://doi.org/10.1016/j.envpol.2018.03.026.

Zhou, Q., Zhang, H., Fu, C., Zhou, Y., Dai, Z., Li, Y., Xue, Y., Fu, C., Tu, C., Luo, Y., 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma. 322, 201-208. https://doi.org/10.1016/j.geoderma.2018.02.015.

Zhou, Q., Zhang, H., Zhou, Y., Li, Y., Xue, Y., Fu, C., Tu, C., Luo, Y., 2016. Separation of microplastics from a coastal soil and their surface microscopic features. Chin. sci. bull. 61(14), 1604-1611. https://doi.org/10.1360/N972015-01098.

Zhu, B. K., Fang, Y. M., Zhu, D., Christie, P., Ke, X., Zhu, Y. G., 2018a. Exposure to nanoplastics disturbs the gut microbiome in the soil oligochaete Enchytraeus crypticus. Environ. Pollut. 239, 408-415. https://doi.org/10.1016/j.envpol.2018.04.017.

Zhu, D., Chen, Q. L., An, X. L., Yang, X. R., Christie, P., Ke, X., Wu, L. H., Zhu, Y. G., 2018b. Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. Soil Biol. Biochem. 116, 302-310. https://doi.org/10.1016/j.soilbio.2017.10.027.

Zhu, F., Zhu, C., Wang, C., Gu, C., 2019. Occurrence and ecological impacts of microplastics in soil systems: a review. Bull Environ Contam Toxicol. 102(6), 741-749. https://doi.org/10.1007/s00128-019-02623-z.

Zubris, K. A. V., Richards, B. K., 2005. Synthetic fibers as an indicator of land application of sludge. Environ. Pollut. 138(2), 201-211. https://doi.org/10.1016/j.envpol.2005.04.013.

Figure.1: Generation and dispersion of microplastics in terrestrial environments. (adapted and modified from **Karbalaei et al., 2018**)

Figure.2: Compost is one of the major sources of MPs and NPs input to agricultural soils (picture taken in Australia by the authors).

Figure.3: Schematic representation of microplastics extraction from soil sample (adapted and modified from **He et al., 2018a**)

Figure.1:


Medical application and pharmaceuticals
Personal care cosmetics
Particulate emission and domestic washing
Physical and chemical weathering
Transport and urban infrastructure
During maintenance and manufacturing process
Landfill
Shipping, transportation recreational activities
Erosion and tire abrasion
Sewage treatment plants
Terrestrial food chain transfer and transport by soil animals
Agriculture (potential plant uptake)
Biological plastic fragmentation

Figure.2:

Figure.3:

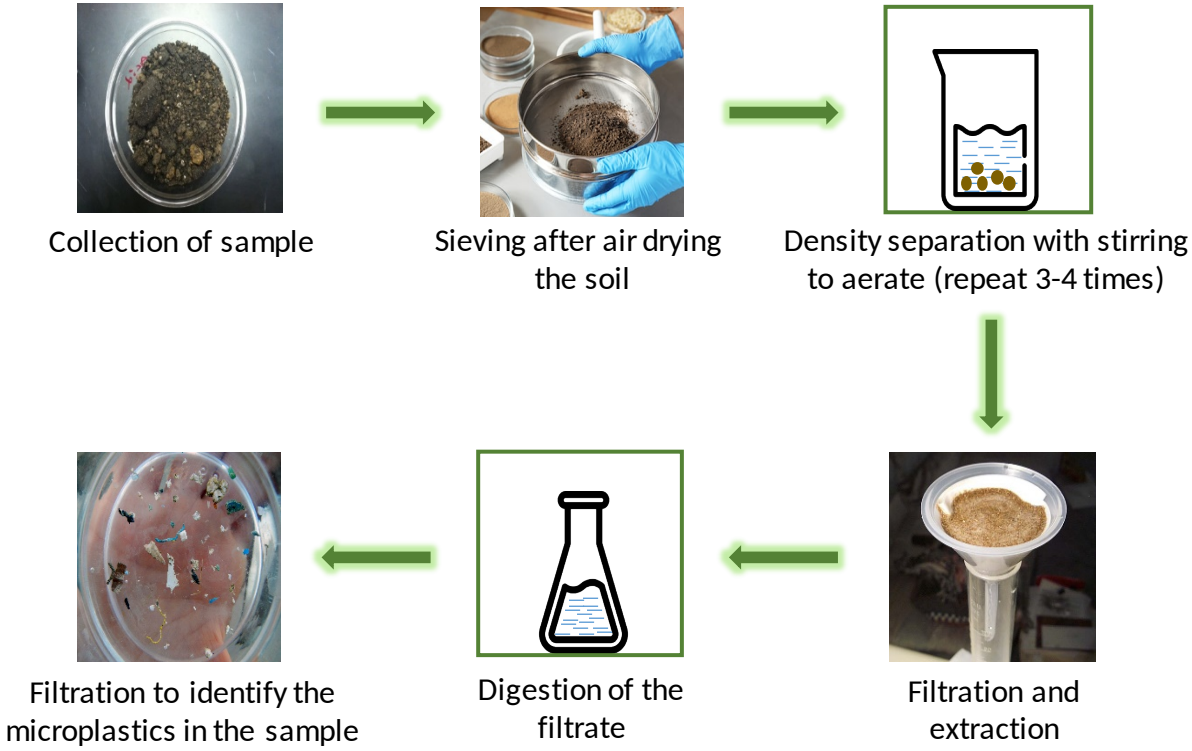
Collection of sample
Sieving after air drying the soil
Density separation with stirring to aerate (repeat 3-4 times)
Filtration and extraction
Digestion of the filtrate
Filtration to identify the microplastics in the sample

Table.1: Representation of waste management statistics and plastic waste estimates released to freshwater (continental) and terrestrial environments [based on figures for European Union (EU)].

Table.2: Occurrence and characteristics of microplastics in terrestrial environments.

Table 3. Additives/chemicals used in manufacturing and processing of the plastics.

Table.4: Analytical techniques for Identification and characterization of MPs and its advantages and disadvantages.

Table.1:

Plastic (handling/disposal)	**Plastic (million metric tons/year)**	**Reference**
Plastic production (EU total, 2014)	59	**(PlasticsEurope, 2015)**
Plastic waste (EU total, 2014)	25.8	**(PlasticsEurope, 2015)**
Managed plastic waste (−2% mismanaged waste)	25.28	**(Nizzetto et al., 2016b)**
Mismanaged plastic waste (2% of plastic waste in the EU)	0.52	**(Horton et al., 2017b; Jambeck et al., 2015)**
Total mismanaged plastic waste outstanding in continental environments (EU)	0.47–0.91	**(Horton et al., 2017b)**
Landfill (EU total)	8	**(PlasticsEurope, 2015)**
Recycling (EU total)	7.6	**(PlasticsEurope, 2015)**
Energy recovery (EU total)	10.2	**(PlasticsEurope, 2015)**
Plastic in sewage sludge (EU total)	0.063–0.43	**(Nizzetto et al., 2016b)**
Ocean input (EU total)	0.04–0.11	**(Jambeck et al., 2015)**

Table.2:

Soil source/Soil type	Country and location	Abundance	Composition	Size range (mm)	Shape	Reference
Rice-fish coculture ecosystems	China (Shanghai)	10.3 ± 2.2 item kg^{-1}	PE, PP	< 1	Mainly fibers	**Lv et al., 2019**
Vegetable fields	China (Shanghai)	78.00 ± 12.91 62.50 ± 12.97 item kg^{-1}	PE, PP, Polyethersulfone (PES)	0.03-16	Fiber, film, fragment	**Liu et al., 2018**
Agricultural field	China (Loess plateau)	<0.54 mg kg^{-1}	PE, PP	> 0.1	-	**Zhang et al., 2018b**
Tree planted soils	China (Yunnan)	7100-42,960 item kg^{-1}	-	0.05-10	Mainly fibers	**Zhang and Liu, (2018)**

Beach soil	China (Hebei)	317 item/500 g (average)	-	1.56 ± 0.63	Fragments, granules, fibers and films	**Zhou et al., 2016**
Coastline soil	China (Shandong)	1.3-14,712.5 item kg^{-1}	PP, PE, PES, polyether urethane	60% in size of <1 mm	Foams, fibers, pellets, flakes, fragments, films and sponges	**Zhou et al., 2018**
Industrial soil	Australia (Sydney)	300-67,500 mg kg^{-1}	PE, PS, PVC	-	-	**Fuller and Gautam, (2016)**
Floodplain soil	Switzerland	up to 55.5 mg kg^{-1}or 593 item kg^{-1}	PE, PS, PVC	< 0.5	-	**Scheurer and Bigalke, (2018)**

Table.3:

Types of additives/chemicals	Example	Function	Reference
Lubricants	Molybdenum disulfide and graphite	Flexible plastic manufacturing used in squeeze bottles and fiber	**(Biron, 2003)**
Flame retardants	Decabromodiphenyl ether	Improve the safety index of cultured marble and cable coverings	**(Strååt & Nilsson, 2018)**
Antioxidants	Tris(2,4-di-tert-butylphenyl) phosphite, Pentaerythritol tetrakis (3,5-di-tert-butyl-4-hydroxyhydrocinnamate)	Deal with resistance against weathering and useful in plastic processing	**(Hansen et al., 2013; Hahladakis et al., 2018)**
Anti-statics	Glycerol monostearate, Indium tin oxide	Generate static electricity attraction (reduce dust collection)	**(Gächter et al., 1993)**

Foaming agents	Isocyanate, Chlorofluorocarbons	Useful in the production of building board, polystyrene cups and polyurethane carpet underlayment	**(Gächter et al., 1993)**
Antimicrobials	2,4-dichloro- 6-(3,5-dichloro- 2-hydroxyphenyl) sulfanylphenol	Production of wall coverings (Bithionol) and shower curtains; control formation of biofilm	**(Gächter et al., 1993)**
Plasticizers	Bis(2-ethylhexyl) phthalate	Utilized in gutters, wire insulation and flooring owing to slow decomposition from light	**Bhunia et al., 2013; Sablani & Rahman, 2007)**
Colorants	Sudan stain, Diarylide pigment	Useful in coloring plastic products	**(Biron, 2003; Hahladakis et al., 2018)**

Table.4:

Technique	Particle size range	Methodology	Advantages	Limitations	Reference
Spectroscopic					
μ-FTIR	Particles > 500 μm and smaller to 20 μm can be investigated by ATR-FTIR and microscopy coupled FTIR respectively.	Depending on the molecular structure and composition of the substance, samples are exposed to defined range of IR-radiation.	Emerging, quick, and reliable nondestructive method.	Only for IR active sample, difficult to analyze nontransparent particle and particles below 20 μm, pretreatment required expensive.	**(Li et al., 2018; He et al., 2018a)**
μ-Raman	Particles size > 1 μm but also works for 1 to 20 μm	The shift in Raman spectra can be measured, that provided substance specific spectra.	Analyzed particle size 1-20 μm. Nontransparent, dark particles can be analyzed.	Samples required refinements before analysis, time intensive procedure.	**(Li et al., 2018; He et al., 2018a)**

SEM	Even microscale particles can be analyzed	Generated electron interacts with the sample which eventually measures the secondary ions.	Generate high resolution images	Samples required coating, less informative.	**(Bläsing & Amelung, 2018; Zhou et al., 2018; de Souza Machado et al., 2018a)**
Chromatographic					
Pyrolysis GC-MS	Works well with particles size > 500 µm.	The GC column coupled to a quadrupole – MS. the generated spectra are identified comparing with available common plastic database.	It is quite sensitive, easier and reliable method which avoids possible background contamination	The plastics database is limited, single sample at a time with certain weight. single sample at a time with certain weight.	**(Dümichen et al., 2017; Ivleva et al., 2017)**
Liquid Chromatography (LC)	Applied for large sample large sample size.	Samples are prepared in selective for analysis.	Selected polymers displayed better recovery.	Restricted to specific polymers (PE and PET), not recommended for environmental samples.	**(Hintersteiner et al., 2015; Elert et al., 2017)**

Visual					
Microscopic Counting	Stereomicroscope can identify particles size down to µm.	The particles are counted directly and identified.	Cost effective, faster and easier.,	It cannot determine the nature of the sample.	**(He et al., 2018a)**
Tagging	Microscale MPs can be counted and visualized.	MPs are irradiated with blue light and adsorption of hydrophobic dye is done which renders them fluorescent.	It is a quick, inexpensive, and easier.	Impurities in the samples may leads to overestimation of MPs.	**(Shim et al., 2016; He et al., 2018a)**