Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 23 | No. 4 | pp. 2143-2155 | 2024

Review Research Paper

https://doi.org/10.46488/NEPT.2024.v23i04.019

Open Access Journal

Microplastics in Agricultural Soil and Their Impact: A Review

P. Solanki[1]†, S. Jain[1], R. Mehrotra[2], P. Mago[2] and S. Dagar[3]
[1]IGNOU, Dyal Singh College, Delhi, India
[2]Shaheed Rajguru College of Applied Science for Women, University of Delhi, Delhi, India
[3]Department of Environmental Engineering, Delhi Technological University, Delhi, India
†Corresponding author: Pooja Solanki; solankipooja8@gmail.com

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 19-03-2024
Revised: 07-05-2024
Accepted: 18-05-2024

Key Words:
Microplastics
Agricultural soil
Sludge
Sewage
Microbes
Soil health

ABSTRACT

The rapid global plastic production of 348 million tonnes in 2018 has led to widespread environmental pollution, especially in terrestrial ecosystems. This study examines microplastics in agricultural soils, coming alarmingly. Particles ≤5 mm, which are defined as microplastics, have detrimental effects on the earth's environment. Because of its ecological importance, soil acts as an important microplastic sink, affecting soil and plant health and microbial activity. A variety of factors contribute to microplastic pollution in agricultural soils, including plastic mulching, manure, agricultural products (silage nets, twine), sewage sludge, weathering, and other indirect processes. These microplastics migrate, threatening soil integrity and biodiversity. Soil microplastics are analyzed for size, volume fraction, and polymer. Common materials include polyethylene, polypropylene, polyamide, polystyrene, polyvinyl chloride, and polyesters. Techniques, including optical microscopy and spectroscopy, extract and analyze microplastics. This comprehensive review calls for increased concern about the ecological effects of microplastics in agricultural soils. It emphasizes the importance of managing plastics to solve environmental challenges. The integrated environmental assessment highlights the complex relationship between microplastics and soil ecosystems, providing insights into potential risks and suggesting strategies to combat this looming environmental threat.

INTRODUCTION

Plastic is a flexible, long-lasting, and cost-effective material used in a variety of important industries such as packaging, electronics, agricultural production, etc. (Plastic Europe 2018). The widespread use of these synthetic materials increased manufacturing, resulting in a huge amount of plastic litter in the environment (Geyer et al. 2017). In 2018, the anticipated global plastic production was 348 million tonnes (Plastic Europe 2018). Around ≥6000 Mt of plastic garbage was generated in 2015, with around 80% of the material ending up being dumped directly into the environment that finds its way to landfills (Geyer et al. 2017). It is also observed that around 8078 Mt of Plastic has been generated in the last 50 years between 1950 and 2020 (Plastic Europe 2021). Plastic waste is ubiquitous and has been discovered in a variety of environmental compartments (de Souza Machado et al. 2018a), where it is subjected to increasing fragmentation caused mostly by thermo-oxidation, photo-oxidation, UV light, and mechanical abrasion (Wang et al. 2019, Hayes 2019 & Da Costa et al. 2019). Unfortunately, the fragmentation process does not entirely disintegrate the plastic waste but instead transforms it into a plethora of fine-sized plastic particles, encompassing Microplastics defined as 5 mm in diameter (Arthur et al. 2009, Thompson et al. 2004).

CHARACTERISTIC FEATURES OF MICROPLASTICS

The sink of Microplastics discovered in the soil can indicate localized usage, adjacent artificial activities, or atmospheric deposition, but the soil is a potential sink for Microplastics from different sources (Forster et al.2020). The capacity to understand the formation of Microplastics in soil, where the distribution distance on both temporal and spatial scales, among the point of origin and the sampling site, may be shorter than that in atmospheric transfer, is made possible by correlations among different kinds and occurrences of Microplastics discovered and regional human activities (Eerkes-Medrano et al. 2018, Luo et al. 2020). Additionally, the effects of different types of Microplastics on terrestrial systems vary (de Souza Machado et al. 2019, Lozano et al. 2020).

Shape

According to researchers (Xu et al. 2020, Yang et al. 2021), the Microplastics seen may be divided into numerous shapes, including pellets, fragments, foam, fiber, and film. According to a laboratory weathering experiment, PP pellets may create 6084±1061 particles after being subjected to UV light for 12 months and mechanical abrasion for 2 months (Yang et al. 2021).

In addition to being the master batch for products like industrial pellets, pellet particles are also connected to personal care items like cosmetics and cleaning supplies (Xu et al. 2020). Additionally, a new class called "fiber balls" is created since fibers frequently tangle and form balls. Such a fiber ball often comes in bundles and is made up of fibers in various colors (Weber & Opp 2020).

Size Fractions

The definition of Microplastics by researchers, as well as the sensitivity of the extraction and analytical techniques utilized, makes determining the size of Microplastics fairly challenging. The concept of Microplastics has become clearer as a result of an early study that focused on their presence in aquatic ecosystems. Microplastics are known to have a size of less than 5 mm. However, the sampling, pretreatment, and identification procedures directly affect the minimum particle size (Yang et al. 2021, Weber & Opp. 2020). In soil environments, Microplastics with minute particle sizes (≤ 1 mm) have been commonly reported.

Polymer Identification

According to the study of Yang et al. (2021), the presence of Microplastics is crucial for determining the source of contamination. Polyethylene, polypropylene, polyvinyl chloride, polyamide, polystyrene, and polyester are the most prevalent polymers found in soil. Polyethylene and polypropylene are the most commonly found in soil.

Microplastic pollution has recently received a lot of attention both from the general public as well as scientific communities all over the world, with a focus on aquatic settings, particularly the marine environment (Hidalgo-Ruz et al. 2012, Auta et al. 2017). The availability of Microplastics in the oceans has been linked mostly to ongoing inputs and also the degradation and fragmentation of large plastic litter (Hidalgo-Ruz et al. 2012), the vast majority of which are emitted from land (Rezania et al. 2018).

Microplastics in aquatic conditions may be consumed by Oligochaeta, crustacea, mollusks, nematodes, and vertebrates (Jambeck et al. 2015, Desforges et al. 2015, Hurley et al. 2007, Lei et al. 2018b). Microplastics and plastic-derivative compounds, such as plastic additives and adhered contaminants, have been linked to diversified toxicological effects that include inflammatory responses, metabolic disorders, stunted growth and reproduction issues, and other lethal issues (Hurley et al. 2007). Such circumstances are also likely for soil biota. Microplastics have been a research-intensive subject in aquatic environments for over a decade (Van Cauwenberghe et al.2015, Akdogan & Guven et al. 2019, Rillig 2018, Cole et al. 2014, Riilig & Bonkowski 2018, Cozar et al. 2014, Ivleva et al. 2017).

Microplastics accumulate more in terrestrial soil than in aquatic habitats (Zhao et al. 2018). As per UNEP reports, substantial amounts of particle plastics observed in the marine environment worldwide originate from land-based sources (UNEP, 2016). According to Rezania (2018), around 4.8 - 12.7 Mt of terrestrial plastic garbage is found entering the ocean every year, accounting for approximately 1.7-4.6% of total plastic waste generated globally. Sediment transmission during soil erosion is an event that permits particle plastics to be transported from terrestrial to aquatic habitats. Despite this connection to terrestrial resources, numerous scientific studies on the particles of plastic have overlooked the consequences of these synthetic materials (Bolan & Bradney 2019). Given that the majority of plastic waste is generated and discharged on land, it is surprising that Microplastics research has only recently begun to focus on terrestrial systems, where soil appears as a long-term sink for Microplastics debris (Kumar et al. 2020, Moller et al. 2020, Rochman 2018). Terrestrial domains, such as soils, are more vulnerable to plastic contamination than the oceans. According to Nizzetto et al. (2016), the annual input of Microplastics from sewage and wastewater treatment sludge on agricultural fields could exceed the total amount of Microplastics currently floating in the global oceans. Although the underlying mechanisms are unknown, preliminary data suggest that the presence of Microplastics in soils may impact the soil properties, plant performance, and microbial activity (de Souza Machado et al. 2019).

Recent research has discovered a considerable amount of filamentous and fragmented Microplastics in soils all around the world (Zhao et al. 2018). For example, recently discovered fragmented-dominated Microplastics in agricultural soils, where sewage sludge application promotes a Microplastics buildup (van den Berg et al. 2020). Microplastics accumulated in the soil can be easily taken up by plants and transferred through the food chain (Guo et al. 2020).

Although the genesis and potential translocation pathways of Microplastics in soil are varied, including the use of sewage-generated sludge and organic compost (Huerta

Lwanga et al. 2017), irrigation (Blasing & Amelung 2018), plastic mulching (Yang et al. 2021), littering (Akdogan & Given 2019), and atmospheric deposition (Allen et al. 2019), urban soil used for agriculture is more prone to Microplastics pollution since they are often exposed to Microplastics (Moller et al. 2020, Chase et al. 2018).

Microplastics have been shown to harm soil health and function (de Souza Machado et al. 2018b, Liu et al. 2018), as well as in marine environments. Contamination will certainly result in inadvertent Microplastics ingestion by soil fauna. Worms, including Earthworms and ringworms, have been shown to consume Microplastics, with the rate increasing substantially as the amount of Microplastics rises; for example, Huerta Lwanga et al. (2017) detected around 14.8-28.8 Microplastics particles/gram of earthworm casts and 129.8- 82.3 particles/grams of chicken feces in home garden soils. Panebianco et al. (2019) discovered Microplastics in the majority of the snails (a total of 425 specimens), with an average of 0.92-1.21 particles/5 snails.

Plastic trash, particularly biodegradable plastics, is more prone to physical fragmentation than decay by mineralization, resulting in smaller plastic sizes. Natural disintegration and degradation of Microplastics can produce plastic particles as small as 0.1 mm in diameter, known as nano-plastics (NPs)(de Souza Machado et al. 2018a, 2018b). The plastics gradually weather and accumulate in the soil, contaminating the soil with Microplastics fragments. Furthermore, the recent increase in the number of waste sites has made soil huge Microplastics sink. Microplastics migration in soil happens both vertically as well as horizontally, i.e., they are conveyed to people and animals horizontally via the terrestrial food chain and drain down vertically into groundwater with run-off. Microplastics have also been identified in sheep faces, which were most likely biomagnified by feed and the surrounding environment (Beriot et al. 2021).

In agricultural fields, plastic mulching is widely used across the world to boost yields, improve fruit quality, and improve water usage efficiency (Ashrafuzzamann et al. 2011). Furthermore, due to their specific optical and material properties, plastic mulches are employed globally (Chalker-Scott et al. 2007). Besides this, the use of organic fertilizers and films made up of plastic in agricultural operations is the primary cause of Microplastics (MP) buildup in farms (Weithmann et al. 2018).

A study by Kumar et al. (2021) shows that plastic mulching has been detected in four locations for producing vegetables viz tomatoes and beans in different regions of Tamil Naidu, India. The soil from the Sulur region had more plastic residues than the soil compared to the other areas. At a depth of 0-10 cm, the plastic content of the soil taken from Sulur varied from 0.092 ± 0.02 to 4.96 ±0.08 g kg^{-1} soils. The plastic content varied from 0.075 ± 0.01 to 3.45 ± 0.01 at a depth of 11-20 cm. At a depth of around 21-30 cm, the plastic content was determined to be in a range of 0.01 ± 0.02 to 2.81± 0.01 g kg^{-1} soils.

SOURCES OF MICROPLASTICS IN AGRICULTURAL SOIL

Microplastic sources are primarily characterized as either primary or secondary (Cole et al. 2011, Thompson & Richard 2015). Primary Microplastics are designed with specific applications in mind, such as cosmetic harsh chemicals, drug vectors, and engineering-related uses such as air blasting (Auta et al. 2017, Hays et al. 1974). Microplastics are difficult to eliminate utilizing sewage disposal systems, and once they enter the wastewater, they eventually accumulate in the environment (Van Cauwenberghe et al. 2015).

Secondary Microplastics are formed when bigger plastics are gradually shattered into smaller bits by a variety of complicated environmental factors, including wave action, temperature of wind, and UV radiation (Andrady 2011, Rocha-Santos & Duarte 2015). Repeated usage of products made of plastics can induce fragmentation and the development of additional Microplastics (Hartline et al. 2016). Furthermore, plastic emissions from vehicle transportation, such as wearing and tearing of tires, brakes, and road markings, are major contributors to Microplastics in the natural environment (Gieré et al. 2018). The World average of Microplastics emissions from road vehicle tire abrasion was calculated to be 0.81 $kg.year^{-1}.capita^{-1}$ (Kole et al. 2016). Aside from Vehicles, abrasion from aircraft tires accounts for around 2% of total tire disintegration emissions in the Netherlands (Kole et al. 2016).

Furthermore, artificial grass is a major secondary source of Microplastics, with estimates ranging from 760-4500 $t.y^{-1}$ (Kole et al. 2016, Lassen et al. 2015, Magnusson et al. 2016) result, many types of Microplastics are discharged into natural environments and ecosystems. Compared to the sources of Microplastics in the ocean, which primarily include land-based sources (80%), tourism on the coast, recreational and commercial fishing gear contributing 18%, shipping and marine industries (e.g., aquaculture, oil rigs, etc.) (Cole et al. 2011, Hays & Cormons 1974, Kole et al. 2016). Microplastics enter soil through a variety of pathways, including landfills (He et al. 2019), amendments of the soil (Zubris et al. 2005), sewage sludge land application (Corradini et al. 2019, Mintenig et al. 2017, Ziajahromi et al. 2017), wastewater irrigation. Furthermore, plastic debris in soil also fragments into Microplastics by the actions of soil fauna, such as feeding, digesting, and excretion (Chae et al. 2018).

Direct Sources/Primary Sources of Microplastics in Agricultural Oils

Plastic Mulching

Massive but undetectable sources of plastics are continually flooding the soil, causing Microplastics deposition, but with no obvious ability to stop or disrupt them. Mulch film, which is made of polyvinyl chloride and polyethylene, has become a popular technique in worldwide agriculture because of its numerous economic benefits, including increased harvest, enhanced quality of fruits, and water use efficiency (Yang et al. 2021). In 2016, the worldwide market for agricultural films made of plastic was 4 million tonnes, and it is predicted to rise at a pace of 5.6 percent per year by 2030 (Jambeck 2015).

Large chunks of plastic mulch debris lying on the farm land's surface are naturally exposed to UV light, producing photo-degradation and becoming brittle (Astner et al. 2019). Shear pressures on plastic trash in farmland will also be felt when agricultural soils are plowed and cultivated, potentially fragmenting already fragile polymers (Piehl et al. 2018).

According to the study by Kumar et al. (2021), Microplastics are found in the 3 regions of India in the amount of 37.97%, 35.07%, and 36.99% of the tomato fields that use the process of Plastic Mulching in Fig. 1.

Littering

The excessive growth of plastics and unplanned or poor management procedures have increased the presence of a large variety and range of Microplastics waste in the soil (Akdogan & Given 2019, Kumar et al. 2020). Microplastics in aquatic environments can emerge from a substantial volume of plastic trash (Blasing et al. 2018). From the 1950s till 2015, roughly 6.3 Bt of plastic rubbish was created globally, with 4.97 Bt ending up in landfills and natural habitats (Geyer et al. 2017).

Silage and Bale Nets

In the first research addressing the issue of the presence of Microplastics in soils at an agricultural scale, (Piehl et al. 2018) indicated the pollution of livestock feeds due to the use of plastics in the form of wrapped grass bales and silage after intake, may enter the soil through excretion.

Twine

The twine composed of Polypropylene (PP) is used for various agricultural uses (Guerrini et al. 2017). Twine helps to secure plants to stakes for significant crops, including tomatoes, crucifers, sweet peppers, etc. It is utilized in the cultivation of bananas to connect plants and keep them from toppling over (Hernandez & Witter 2016). During harvesting, the twine is cut and frequently dumped carelessly in the fields only, where it ends up in the form of Microplastics in the soil. There are initiatives to promote the use of biodegradable twine, which may be gathered along with plant leftovers and composted (Guerrini et al. 2017, Biothop 2019).

Plastics Used for Plant Protection

Plastic films, along with non-woven textiles made of plastic, such as those utilized in greenhouses, polytunnels, shade

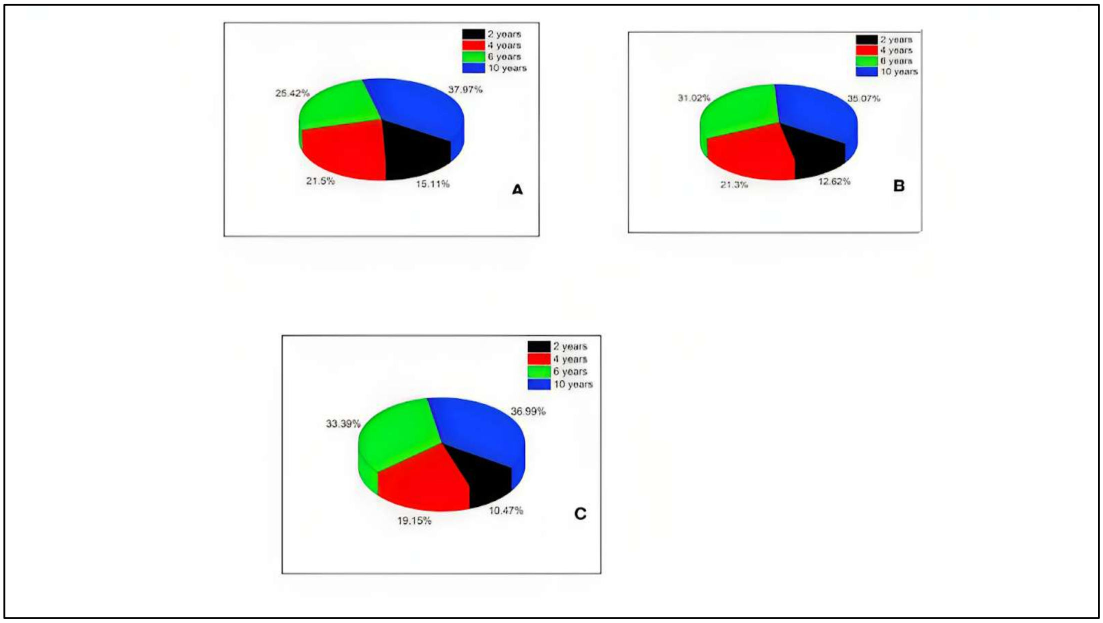

Fig. 1: Effect of the duration of plastic film mulching on percent distribution of plastic residues at different soil depths (A) 0-10 cm (B) 11-20 cm (C) 21-30 cm by Kumar et al. (2021).

nets, and also as wind barriers, enhance the presence of Microplastics in soil samples. Liu (2021) reported that for an identical productive area, samples of soil collected from farms without greenhouses contained fewer Microplastics compared to soil samples collected from farms with greenhouses. At fields where greenhouses were initially utilized in the 1980s, the authors recorded a range of 1000 - 3786 particles of MP kg^{-1}. Liu (2021) also observed an average of 2110 MP kg^{-1} in soil samples collected within greenhouses compared to 310/kg Microplastics in soil samples collected outdoors.

Improper Storage

According to Svensk Ensilageplast Retur, Plastic may be found in abundance on an agricultural farm. Farmers have to put additional efforts into collecting and storing old plastics since they frequently lack the time or technical competence to securely clean and preserve the used ones. To keep plastic garbage clean and avoid it from blowing away, it must be deposited in a dry spot that is shielded from the wind. Plastic waste management in agricultural regions is a major problem, which can be ascribed in part to inappropriate plastic storage on farms.

Indirect Sources/Secondary Sources of Microplastics

Sewage Sludge

Sludge from sewage and wastewater treatment plants causes Microplastics contamination, and Microplastics can build in soil with repeated sludge use (Xu et al. 2021). Microplastics enter wastewater treatment facilities via a variety of routes (Gao 2018). Micro beads from personal cleaning and care products, polymer fibers released from washing textiles, plastic masterbatches seeped from the plastic production facility, and Microplastics from automobile tires are all transmitted to sewage. These tiny particles flow and settle throughout the sewage treatment process. A portion of them is released from the sewage system, while the majority is segregated during the sewage treatment sedimentation process and eventually enters the wastewater sludge (Gao 2018).

Compost

Compost soil addition can potentially provide a conduit for Microplastics to enter the soil. Organic waste is often placed in fields as nutrients after it has been composted and fermented for reuse nutrients, minerals, trace elements, and humus. Composts made from biological waste, for example, have been shown to include plastics as a result of improper disposal and insufficient waste categorization (Blasing & Amelung 2018). The concentration of plastic pieces detectable to the human eye in a composting factory in Bonn is 2.38 to 180 mg kg^{-1}, confirming the presence of Microplastics in organic compost (Blasing & Amelung 2018). Weithmann et al. (2018) discovered that the compost from municipal organic waste and green clipping in German contained 24MP particles/kg ranging in size from 1mm to 5mm. Furthermore, according to (Crossman 2020), despite compliance with current regulations, biosolid applications may result in significant rates of Microplastics export. Liu (2021) discovered that total Microplastics concentrations in soils are 545.9 and 87.6 items/kg after yearly launch with 30 and 15 t ha^{-1} of sludge composts, respectively, which is considerably higher than soil lacking compost application.

Irrigation

The presence of Microplastics in agricultural irrigation water resources has been widely verified (Jian et al. 2020). Rivers, lakes, reservoirs, and aquifers are the primary irrigation water sources worldwide. Sewage is also utilized for irrigation in some locations when water resources are restricted (Blasing & Amelung 2018). Despite the fact that a substantial number of Microplastics may be eliminated during the sewage treatment process, high quantities of Microplastics remain in the purified wastewater (Ziajahromi 2017). Several studies have shown significant amounts of Microplastics in rivers, lakes, reservoirs, and aquifers (Koelmans et al. 2019). Microplastics contained within water reservoirs will be transported to the soil by irrigation, creating a pedigree of Microplastics in the soil.

Flooding and Street Runoff

Street runoff and floods, in addition to purposeful irrigation, are key channels for the transfer and accumulation of Microplastics into the soil (Blasing & Amelung 2018). Street runoff and floods can introduce unmanaged rubbish dumping near roadways, as well as rubber tire abrasion into soils. Some of them already constitute Microplastics, while others are progressively changed into Microplastics as a result of numerous environmental encounters.

Input From the Atmosphere

Atmospheric transmission is a significant mode of Microplastics deposition to land. A study (Liu et al. 2019) quantified and recorded the first to record and quantify the accumulation of fibrous Microplastics both indoors and outdoors, with the settled flux of atmospheric Microplastics outside reaching 0.3-1.5 fibers m^{-3} (Liu et al. 2019). Every day, relative averages of around 249 fragments, 74 pieces of film, and 43 fibers might be deposited in a distant mountainous catchment region (Allen et al. 2019).

TRANSPORTATION OF MICROPLASTICS TO AGRICULTURAL SOILS

Migration, which includes horizontal and vertical movement as well as biological and non-biological transportation, is a critical link for extending the effect of Microplastics in soil (Xu et al. 2021). Surface runoff or wind can transport Microplastics in surface soil (Koelmans et al. 2019, Qi et al. 2018). The presence of Microplastics in deep soil indicates that Microplastics migrate downhill (Liu et al. 2018). Since Soil is porous, Microplastics in the micrometer (μm) range can be percolated through soil pores via leaching. External pressures such as biological disturbance by the fauna and flora and agricultural operations cause bigger Microplastics to move in the soil.

Also, the bioturbation of plant roots in soil may influence Microplastics translocation through root growth and movement, root water extraction, and furthermore. Soil fauna may help to move Microplastics vertically and horizontally in the soil (Xu et al. 2020). Microplastics have been discovered to be transferred and dispersed by earthworms and collembola species, either by adhesion or excretion (de Souza Machado et al. 2019, Maaß et al. 2017). Furthermore, the formation of fractures in the soil produced by the dry environment allows Microplastics to enter deep soil (Koelmans et al. 2019, Qi et al. 2018).

METHODS TO EXTRACT MICROPLASTICS FROM THE SOIL

Density Separation

The technique of density separation is one of the most often used techniques for separating soil Microplastics. To ensure every particle in the bulk sample sinks or floats, the soil is first treated with ultrasonics (Liu et al. 2018). Sodium chloride is a low-cost, ecologically friendly salt that is commonly used in suspension solutions (Zhou et al. 2018). Yet, the density of a saturated solution of NaCl is 1.2 g cm^{-3}, implying that high-density polymers such as polyvinyl chloride (PVC, 1.35 g cm^{-3}), polyethylene terephthalate (PET, 1.38 g cm^{-3}), and others cannot be separated in this method (Ruggero et al. 2020). As a result, for the suspension medium, several researchers employ a saturated solution of zinc chloride ($ZnCl_2$), sodium iodide (NaI), sodium bromide (NaBr), calcium chloride ($CaCl_2$), and zinc bromide ($ZnBr_2$) (Imhof et al. 2017, Scheurer & Bigalke 2018).

Electrostatic Separation

Plastics are not electrically conductive, unlike soil minerals and other particles. An external electric field can be used to separate the two because of the difference in electrostatic characteristics. Electrostatic separation is a dry processing technology that uses electric forces working on charged particles to separate main and secondary raw materials (Deotterl et al. 2000). It was investigated that plastic particle's electrostatic behavior can be improved before separation from sediment samples using a tiny electrostatic separation apparatus. Without sacrificing Microplastics, up to 99% of the original sample mass might be eliminated (Felsing et al. 2018).

Oil Separation

The lipophilic characteristics of microplastics are used as an alternative to density-based oil recovery technologies in a new, cost-effective oil extraction process (OEP)(Crichton et al. 2017). For seven polymers, the OEP exhibited a recovery ratio of 90-100%, showing a better efficiency than density separation in a salt solution. OEP is less complicated, easier, and less expensive than salt solution separation. However, oil interferes with Fourier Transform Infrared Spectroscopy (FTIR) for identification; thus, a wash with 90% ethanol is required following extraction. Using castor oil, Mani et al. (2019) separated MPs from fluvial suspended surface solids, marine suspended surface solids, marine beach sediments, and agricultural soil substrates. In this investigation, 0.3-1 mm MP particles were extracted utilizing four virgin polymers [polypropylene (PP), polystyrene (PS), polymethyl-methacrylate (PMMA), and glycol-modified polyethylene terephthalate (PETG)]. The average SD MPs spike recovery percentage was 99 4%, with a 95 4% matrix decrease (dry weight, n = 16). This process is less expensive, less risky, and more rapid than salt solution isolation.

Froth Flotation

Froth flotation takes the use of the material's density and the hydrophilic nature of its surface. It is widely employed in the recycling sector. Froth preferentially binds to hydrophobic particles and lifts them upward, segregating them from hydrophilic molecules. To remove plastics from dirt, this approach employs various hydrophilic properties. Plastic flotation techniques include gamma flotation, reagent adsorption, and surface modification (Fraunholcz 2014, Huang et al. 2017) attained a 95% recovery rate for PVC and PMMA by using pinacol (97.71% pure) as the foaming agent and potassium permanganate as the surface modification. In study conducted by Imhof et al. (2017) extracted MPs from sediments using froth flotation but observed low observed found low efficiency and substantial variance across various polymers.

Magnetic Extraction

Grbic et al. (2019) created a magnetic plastic extraction technique in which Magnetized hydrophobic iron nanoparticles are bonded to plastic particles. Iron nanoparticles bond to the surface of Microplastics after being treated with hydrophobic hydrocarbons using cetyl trimethyl silane (HDTMS) and may be retrieved using a magnetic field. Microplastics (polyethylene, polystyrene, polyurethane, PVC, and polypropylene) recovered from fresh water and sediment were 84% and 78%, respectively, spanning particle sizes ranging from 200 m to 1 mm.

ANALYTICAL TECHNIQUES FOR ANALYSIS OF MICROPLASTICS

Identification and quantification of Microplastics from the ambient matrix are required after separation and purification (Kumar et al. 2020). The common strategy is to first identify obvious/possible Microplastics using a microscope, followed by confirmation using spectroscopy and thermodynamic methods such as Fourier Transform infrared spectroscopy (FTIR) or Raman spectroscopies, and Pyrolysis gas chromatography-mass spectrometry (Yang et al. 2021). Optical microscopes, particularly stereomicroscopes, are essential tools for documenting the physical features of Microplastics (Wang et al. 2018a, 2018b)

By using the microscope, the micron (µm) range of the particles can be analyzed. This approach can swiftly identify Microplastics and record their physical properties and abundance. However, Microplastics with diameters of 1 mm are difficult to detect. As a result, only visible Microplastics are easily identified. Furthermore, in order to avoid inaccurate results and other misinterpretations, the technique necessitates labor-intensive pre-concentration and laboratory hygiene. Integrating high-resolution digital cameras into microscopes, on the other hand, allows for the identification of smaller particles as well as the determination of particle size. This approach has the advantage of being non-destructive (Zhang et al. 2019). Unfortunately, visual detection of Microplastics can be occasionally inaccurate (David et al. 2018, David et al. 2019). Additionally, without the assistance of FTIR and Raman spectroscopies, which use their distinctive absorption spectrum to identify the associated functional groups, the microscope can't determine the detailed chemical composition of Microplastics.

Furthermore, without the support of FTIR and Raman spectroscopies, which employ distinctive absorption spectra to identify the relevant functional groups, the microscope cannot detect the exact chemical composition of Microplastics. Optical microscopes, particularly stereomicroscopes, are essential tools for documenting the physical features of Microplastics ((Wang et al. 2018a, Wang et al. 2018b). However, visual assessment alone might result in a large number of false positives, particularly for small fibers. FTIR and its optimization technologies, such as micro-FTIR (- FTIR), attenuated total reflectance FTIR (ATR-FTIR), and focal plane arrays FTIR (FPA-FTIR), thereby demonstrate significantly increased Microplastics characterization capabilities (Wang et al. 2018a, 2018b). These infrared spectroscopic sensors have a detection limit of 5-10 m for Microplastics (Mintenig et al. 2017, Yang et al. 2021). FTIR can identify Microplastics with a particular thickness and has a detection limit of 10 m. The use of ATR-FTIR can benefit from the high signal-to-noise ratio and the extensive literature spectrum (Yang et al. 2021). Focal plane array FTIR can be employed in precision equipment to automatically identify the Microplastics in the sample filter of the preliminary polymer types allocated (Mintenig et al. 2017).

Raman spectroscopy is a further technique for identifying Microplastics. When used in conjunction with a microscope, it can identify Microplastics as tiny as 1 m in size, with spatial resolution reaching as low as 500 nm in some situations (Elert et al. 2017). Another significant benefit of Raman spectroscopy is its ability to analyze wet materials while also identifying fillers or pigments (Dumichen et al. 2017).

Three mass spectrometry analysis methods offer novel approaches for identifying Microplastics (Pual et al. 2019). Pyrolysis-gas chromatography-mass spectrometry (Pyr-GC-MS) (Nuelle et al. 2014), thermo-gravimetric analysis-mass spectrometry (TGA-MS) (Majewsky et al. 2016), as well as thermal extraction desorption-gas chromatography-mass spectrometry (TED-GC-MS) (Pual et al. 2019) have also been demonstrated to be in useful identifying and quantifying Microplastics (Wang et al. 2018). Thermo analytical methods do not need sample pretreatment, and the processed particle size that may be analyzed is limited only by the ability to manually place them into the pyrolysis tube (Zhao et al. 2018). Unfortunately, these procedures remove the Microplastics' color, size, and shape information, which is critical for assessing the potential hazards of Microplastics.

A new approach for size-independent Microplastics analysis has developed (Piehl et al. 2018). Polycarbonate (PC) and polyethylene terephthalate (PET) Microplastics were effectively quantified using the alkali-assisted heating depolymerization technique (Wang et al. 2018). This technology represents a significant advancement in the painstaking separation, recognition, and counting of Microplastics. However, for polymers containing a wide range of important structural components, this technique e requires further validation.

Several technologies, including NIR spectroscopy (Du et al. 2020a), quantitative H-NMR spectroscopy, and hyperspectral imaging technology, offer alternative options for high-throughput Microplastics investigation (Shan et al. 2018). Although these methods need minimum sample preparation, they do have certain intrinsic limitations that may limit their use (Wang et al. 2018a, 2018b). So far, the sensitivity and specificity trials of the integrated NIR spectroscopic chemometric method have failed (Du et al. 2020a). To reduce signal variations, the best setting for the H^{-}NMR approach is to remove any organic debris from the sample (Moller et al. 2020). It is now hard to entirely remove organic materials from environmental samples without destroying the Microplastics, and the application of H^{-}NMR for the examination of soil Microplastics samples is dubious (Moller et al. 2020).

(TOF-SIMS) Time-of-flight secondary ion mass spectrometry might offer information on the Microplastic's size distribution and chemical components (Rillig et al. 2017a). This approach, however, can only be utilized to analyze Microplastics with known composition.

IMPACT AND POTENTIAL RISK OF MICROPLASTICS IN AGRICULTURAL SOIL ECOSYSTEM

Soil nature influences Microplastics migration, and Microplastics change soil properties such as soil structure and functioning as well as the diversity of microbes (Rillig et al. 2017b, Zhang et al. 2018), which may have implications for plant and animal health and pose possible risks for the safety and quality of food, ultimately jeopardizing human health (Rillig et al. 2018). The presence of substantial residual plastic films in soil has been found to reduce soil-saturated hydraulic conductivity and influence soil microbial activity and abundance, thereby influencing soil fertility (Wan et al. 2018).

Impact on Soil Structure

Because Microplastics can interact with different soil features, soil nature may be the fundamental metric for assessing the dangers presented to terrestrial ecosystems by Microplastics (de Souza Machado et al. 2018a). To variable degrees, Microplastics particles may penetrate soil aggregations and clumps: loosely in fragment types and more firmly in linear types (Liu et al. 2018). Furthermore, de Souza Machado et al. (2018b) discovered that polyester fibers may significantly boost capacity while decreasing bulk density and water-stable aggregation; yet, the impacts of polyethylene (PE) and polyacrylic acid on water-holding capacity show no clear trends. As a result, Microplastics of various materials have varying impacts on soil. Microplastics have also been demonstrated to influence soil permeability and water retention, which affects the evaporation of water (de Souza Machado et al. 2018a, Wang et al. 2018). Wan evaluated how the addition of Microplastics affects the evaporation of water and desiccation cracking in two clay soils and found that both are significant and rise with increasing Microplastics concentration (Allison & Jastrow et al. 2006). According to these findings, Microplastics can change the water cycle in soils, increase soil water shortages, and influence pollutant migration into deep soil layers through fissures (Rillig 2018).

Soil Fertility and Nutrient

Soil enzymes with high catalytic capacity are closely associated with a variety of soil biochemical processes; these enzymes serve as an indicator for assessing soil fertility and play an important role in regulating the process of soil nutrient cycling for nutrients like C, N, and P (Trasar-Cepeda et al. 2008, Arthur et al. 2012). Since Microplastics include polymer chains, Microplastics -Carbon may be disguised as a significant caused by human components of the soil organic carbon pool (Rillig 2018). Therefore, according to de Souza Machado et al. (2018b), the impacts of Microplastics on soil are largely dependent on Microplastics content as well as the exposure period.

Soil Microorganisms

According to researchers ((Rillig 2018, Girvan et al. 2003, Naveed et al. 2016, and Rubol et al. 2013), soil characteristics and nutrients are highly linked with soil microbial activity. Changes in the physical environment of the soil, particularly soil aggregation, which has been shown to include linear microfibers (de Souza Machado et al. 2018a, Zhang et al. 2019), are likely to affect microbial development more significantly than non-microfiber-structured soils (Rillig et al. 2017b, Zhang et al. 2018). Furthermore, Microplastics-induced changes in soil porosity and wetness may affect the flow of oxygen in the soil, altering the proportions of anaerobic and aerobic microbes (Veresoglou et al. 2015). Changes in pore spaces induced by Microplastics may also result in the extinction of indigenous microorganisms (Judy et al. 2019). Furthermore, DeForest et al. (2004a) discovered that the addition of Microplastics considerably interacted with the microbial community composition, and the substrate-induced respiration (SIR) levels dramatically dropped, showing that Microplastics generated alterations in soil microbial function. Because Dissolved organic matter (DOM) serves as a substrate and an important source of carbon for microorganisms, it has been linked to both water eutrophication and the greenhouse effect (DeForest et al. 2004b, Marschner & Kalbitz 2003, Alimi et al. 2018). Thus, changes in DOM caused by Microplastics could impact soil function and microbial communities (Judy et al. 2019).

Soil Contamination

The growing prominence of Microplastics as an ecosystem stressor impacts not only soil health and function but also soil biophysical characteristics, resulting in complicated changes in the environmental behavior of other soil contaminants (Wang et al. 2018a, 2018b, Yang et al. 2021, Hahladakis et al. 2018). Due to their high specific surface area and elevated adsorption capacity, Microplastics not only contain additives like diethylhexyl phthalate (DEHP), a common organic pollutant used during the manufacture of plastic (Groh et al. 2019, Brennecke et al. 2016), but they also adsorb dangerous contaminants, such as heavy metals like zinc, copper, and lead, antibiotics, toxic organic chemicals like polybrominated diphenyl ether (PBDE) and perfluorochemicals (PFOS), and PFOS (Gaylor et al. 2013, Li et al. 2018, Lagana et al.2018, He et al. 2018).

Transfer Along Food Chains

The most alarming findings in the research on Microplastics in soil come from the ecological and health concerns posed by Microplastics exposure (Guo et al. 2020, Sarker et al. 2020, Kumar et al. 2020, Schwabl et al. 2019). The concept that Microplastics can be transported from prey (at a lower nutritional level) to a predator (at a higher nutritional level) in the food chain is supported by food chain modeling and field experiments (Guo et al. 2020). Evidence of macro- and Microplastics transmission from soils to chickens in traditional Mayan household gardens in Southeast Mexico is well documented by Huerta Lwanga et al. (2017). Microplastics have recently been found in human feces and adult colectomy tissues, demonstrating their presence in the human digestive system (Ibrahim et al. 2021, Jiang et al. 2019).

Uptake of Microplastics by Plants

According to Zhou et al. (2018), the presence of Microplastics would alter the physical and chemical properties of the soil, which will alter the root system and the vegetative phase and thus impair plant growth. Certain Present studies showed significant effects of Microplastics on plants, including wheat (Triticum aestivum) (Qi et al. 2018), perennial ryegrass (Lolium perenne), Vicia faba (Khalid et al. 2020), Polystyrene Microplastics(PS-MPs) were shown to cause evident growth suppression, genotoxic and oxidative damage to hydroponic Vicia faba, and a substantial number of 100 nm PS-MPs were found to collect in root tips using laser confocal scanning microscopy (Khalid et al. 2020).

Agricultural Production

Soil Microplastics can cause direct crop harm in the early stages by physically blocking the seed capsule openings or roots (Pignattelli et al. 2020). Indeed, with Microplastics exposure, extremely short-term unfavorable impacts on edible plant development may show as early as 6 days after sowing (Napper & Thompson 2019). Furthermore, the extreme durability of polymeric plastic particles hinders breakdown processes; even biodegradable plastic bags stay unchanged after 27 months in soil (Kumari et al. 2022, Silva et al. 2021). The direct absorption of Microplastics from soils through apoplastic and symplastic routes, and by distribution to the plant as a whole through the vascular system, is well documented to affect the development of agriculturally important plants. According to Bouaicha et al. (2022), from the perspective of agricultural output, Microplastics generally have a detrimental influence on crop productivity.

FUTURE CHALLENGES

There are several future challenges associated with Microplastics contamination in the agricultural soil -

- **Widespread Soil Contamination:** The proliferation of microplastics in soil poses an ongoing challenge, as current levels continue to rise due to persistent plastic use and inadequate waste management.
- **Ecosystem Disruption:** Microplastics impact soil ecosystems, potentially altering microbial communities, nutrient cycling, and overall soil health, leading to cascading effects on plant and animal life.
- **Agricultural Concerns:** The use of plastic mulching in agriculture, a primary source of microplastics in soil, presents a dilemma, as alternatives must be developed and adopted to reduce environmental harm without compromising crop productivity.
- **Human Health Risks:** The potential transfer of microplastics through the food chain raises concerns regarding human health impacts. Research is needed to figure out the extent of these risks and implement strategies to minimize exposure.
- **Lack of Comprehensive Regulation:** The absence of strict regulations governing plastic production, use, and disposal contributes to the persistence of microplastic pollution. A coordinated global effort is necessary to address these gaps.
- **Limited Biodegradation:** The slow degradation of plastics exacerbates the persistence of microplastics in the environment. Developing and adopting more biodegradable alternatives is essential for reducing long-term environmental impacts.

REFERENCES

Akdogan, Z. and Guven, B., 2019. Microplastics in the environment: A critical review of current understanding and identification of future research needs. *Environmental Pollution*, 254, p.113011.

Alimi, O.S., Farner Budarz, J., Hernandez, L.M. and Tufenkji, N., 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. *Environmental Science & Technology*, 52(4), pp.1704-1724.

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Jimenez, P.D., Simonneau, A., Binet, S. and Galop, D., 2019. Author Correction: Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience*, 12, pp.339-344.

Allison, S.D. and Jastrow, J.D., 2006. Activities of extracellular enzymes in physically isolated fractions of restored grassland soils. *Soil Biology & Biochemistry*, 38, pp.3245-3256.

Andrady, A.L., 2011. Microplastics in the marine environment. *Marine Pollution Bulletin*, 62, pp.1596-1605.

Arthur, C., Baker, J. and Bamford, H., 2009. The occurrence, effects, and fate of microplastic marine debris. *NOAA*, 11, p.30.

Arthur, E., Moldrup, P., Holmstrup, M., Schjonning, P., Winding, A., Mayer, P. and de Jonge, L.W., 2012. Soil microbial and physical properties and their relations along a steep copper gradient. *Agriculture, Ecosystems & Environment*, 159, pp.9-18.

Ashrafuzzaman, M., Halim, M.A., Ismail, M.R., Shahidullah, S.M. and Hossain, M.A., 2011. Effect of plastic mulch on growth and yield of chili (Capsicum annuum L.). *Brazilian Archives of Biology and Technology*, 54(2), pp.321-330.

Astner, A.F., Hayes, D.G., O'Neill, H., Evans, B.R., Pingali, S.V., Urban, V.S. and Young, T.M., 2019. Mechanical formation of micro-and nano-plastic materials for environmental studies in agricultural ecosystems. *Science of the Total Environment*, 685, pp.1097-1106.

Auta, H.S., Emenike, C.U. and Fauziah, S.H., 2017. Distribution and ecological impact of marine microplastics: A review of scientific evidence. *Environment International*, 102, pp.165-176.

Beriot, N., Peek, J., Zornoza, R., Geissen, V. and Lwanga, E.H., 2021. Low-density microplastics detected in sheep feces and soil: A case study from intensive vegetable farming in southeast Spain. *Science of the Total Environment*, 755, p.142653.

Biothop, 2019. *Biotwine Hop Waste Transformation Into Novel Product Assortments for Packaging and Horticulture Sector*. Biothop.

Blasing, M. and Amelung, W., 2018. Plastics in soil: Analytical methods and possible sources. *Science of the Total Environment*, 612, pp.422-435.

Bolan, N. and Bradney, L., 2019. Particulate plastics in soils. *Chemistry in Australia*, 18.

Bouaicha, O., Mimmo, T., Tiziani, R., Praeg, N., Polidori, C., Lucini, L., Vigani, G., Terzano, R., Sanchez-Hernandez, J.C., Illmer, P. et al., 2022. Microplastics make their way into the soil and rhizosphere: A review of the ecological consequences. *Rhizosphere*, 22, p.100542.

Brennecke, D., Duarte, B., Paiva, F., Cacador, I. and Canning-Clode, J., 2016. Microplastics as vectors for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science*, 175, pp.189-195.

Chae, Y. and An, Y.J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environmental Pollution*, 240, pp.387-395.

Chalker-Scott, L., 2007. Impacts of mulches on landscape plants and the environment - A review. *Journal of Horticulture and Forestry*, 25, p.239.

Cole, M., Lindeque, P., Halsband, C. and Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin*, 62, pp.2588-2597.

Cole, M., Webb, H., Lindeque, P.K., Fileman, E.S., Halsband, C. and Galloway, T.S., 2014. Isolation of microplastic in biota-rich seawater samples and marine organisms. *Scientific Reports*, 4, p.4528.

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E. and Geissen, V., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Science of the Total Environment*, 671, pp.411-420.

Cozar, A., Echevarria, F., Gonzalez-Gordillo, J.I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia-de-Lomas, J., Ruiz, A., Fernandez-de-Puelles, M.L. and Duarte, C.M., 2014. Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences of the United States of America*, 111, pp.10239-10244.

Crichton, E.M., Noel, M., Gies, E.A. and Ross, P.S., 2017. A novel, density-independent, and FTIR-compatible approach for the rapid extraction of microplastics from aquatic sediments. *Analytical Methods*, 9(9), pp.1419-1428.

Crossman, J., Hurley, R.R., Futter, M. and Nizzetto, L., 2020. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Science of the Total Environment*, 724, p.138334.

Da Costa, J.P., Paço, A., Santos, P., Duarte, A.C. and Rocha-Santos, T., 2019. Microplastics in the environment: Challenges in analytical chemistry – A review. *Environmental Chemistry*, 16, pp.145-156.

David, J., Steinmetz, Z., Kučerík, J. and Schaumann, G.E., 2018. Quantitative analysis of poly(ethylene terephthalate) microplastics in soil via thermogravimetry-mass spectrometry. *Analytical Chemistry*, 90, pp.8793-8799.

David, J., Weissmannová, H.D., Steinmetz, Z., Kabelíková, L., Demyan, M.S. and Šimečková, J., 2019. Introducing a soil universal model method (SUMM) and its application for the qualitative and quantitative determination of poly(ethylene), poly(styrene), poly(vinyl chloride), and poly(ethylene terephthalate) microplastics in a model soil. *Chemosphere*, 225, pp.810-819.

de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S. and Rillig, M.C., 2018a. Microplastics as an emerging threat to terrestrial ecosystems. *Global Change Biology*, 24(4), pp.1405-1416.

de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., Becker, R., Gorlich, A.S. and Rillig, M.C., 2019. Microplastics can change soil properties and affect plant performance. *Environmental Science & Technology*, 53(10), pp.6044-6052.

de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R. and Rillig, M.C., 2018b. Impacts of microplastics on the soil biophysical environment. *Biology*, 24, pp.1405-1416.

DeForest, J.L., Zak, D.R., Pregitzer, K.S. and Burton, A.J., 2004a. Atmospheric nitrate deposition and the microbial degradation of cellobiose and vanillin in a northern hardwood forest. *Soil Biology and Biochemistry*, 36, pp.965-971.

DeForest, J.L., Zak, D.R., Pregitzer, K.S. and Burton, A.J., 2004b. Atmospheric nitrate deposition, microbial community composition, and enzyme activity in northern hardwood forests. *Soil Science Society of America Journal*, 68, pp.132-138.

Deotterl, M., Wachsmuth, U., Waldmann, L., Flachberger, H., Mirkowska, M., Brands, L., Beier, P.-M. and Stahl, I., 2000. Extraction and identification methods of microplastics and nanoplastics in agricultural soil: A review. *Journal of Environmental Management*, 294.

Desforges, J.P., Galbraith, M. and Ross, P.S., 2015. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Environmental Contamination and Toxicology*, 69, pp.320-330.

Doyle, M.J., Watson, W., Bowlin, N.M. and Sheavly, S.B., 2011. Plastic particles in coastal aquatic ecosystems of the Northeast Pacific Ocean. *Marine Environmental Research*, 71(1), pp.41-52.

Du, C., Liang, H., Li, Z. and Gong, J., 2020a. Pollution characteristics of microplastics in soils in southeastern suburbs of Baoding City, China. *International Journal of Environmental Research and Public Health*, 17, p.845.

Dumichen, E., Eisentraut, P., Bannick, C.G., Barthel, A.K., Senz, R. and Braun, U., 2017. Fast identification of microplastics in complex environmental samples by a thermal degradation method. *Chemosphere*, 174, pp.572-584.

Eerkes-Medrano, D. and Thompson, R., 2018. Occurrence, fate, and effect of microplastics in freshwater systems. *Environmental Pollution*, pp.95-132.

Elert, A.M., Becker, R., Duemichen, E., Eisentraut, P., Falkenhagen, J., Sturm, H. and Braun, U., 2017. Comparison of different methods for microplastic detection: What can we learn from them, and why asking the right question before measurements matters? *Environmental Pollution*, 231, pp.1256-1264.

Felsing, S., Kochleus, C., Buchinger, S., Brennholt, N., Stock, F. and Reifferscheid, G., 2018. A new approach in separating microplastics from environmental samples based on their electrostatic behavior. *Environmental Pollution*, 234, pp.20-28.

Forster, N.A., Tighe, M.K. and Wilson, S.C., 2020. Microplastics in soils of wilderness areas: What is the significance of outdoor clothing and footwear? *Geoderma*, 378, p.114612.

Fraunholcz, N., 2014. Separation of waste plastics by froth flotation - A review, Part 1. *Minerals Engineering*, 17(2), pp.261-268.

Gao, H., Yan, C., Liu, Q., Ding, W., Chen, B. and Li, Z., 2018. Effects of plastic mulching and plastic residue on agricultural production: A meta-analysis. *Science of the Total Environment*, 651, pp.484-492.

Gaylor, M.O., Harvey, E. and Hale, R.C., 2013. Polybrominated diphenyl ether (PBDE) accumulation by earthworms (Eisenia fetida) exposed to biosolids-, polyurethane foam microparticle-, and penta-BDE-amended soils. *Environmental Science and Technology*, 47, pp.13831-13839.

Geyer, R., Jambeck, J.R. and Law, K.L., 2017. Production, use, and fate of all plastics ever made. *Science Advances*, 3, pp.1-5.

Gieré, R., Sommer, F., Dietze, V., Baum, A., Gilge, S., Sauer, J. and Maschowski, C., 2018. Tire abrasion is a major source of microplastics in the environment. *Geological Society of America*, 50, p.6.

Girvan, M.S., Bullimore, J., Pretty, J.N., Osborn, A.M. and Ball, A.S., 2003. Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. *Applied and Environmental Microbiology*, 69, pp.1800-1809.

Grbic, J., Nguyen, B., Guo, E., You, J.B., Sinton, D. and Rochman, C.M., 2019. Magnetic extraction of microplastics from environmental samples. *Environmental Science & Technology Letters*, 6(2), pp.68.

Groh, K.J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P.A., Lennquist, A., Leslie, H.A., Maffini, M., Slunge, D., Trasande, L., Warhurst, A.M. and Muncke, J., 2019. Overview of known plastic packaging-associated chemicals and their hazards. *Science of the Total Environment*, 651, pp.3253-3268.

Guerrini, S., Borreani, G. and Voojis, H., 2017. Biodegradable materials in agriculture: Case histories and perspectives. In: Malinconico, M. (Ed.), *Soil Degradable Bioplastics for Sustainable Agriculture*. Springer, Berlin Heidelberg, pp.35-65.

Guo, J.J., Huang, X.P., Xiang, L., Wang, Y.Z., Li, Y.W., Li, H., Cai, Q.Y., Mo, C.H. and Wong, M.H., 2020. Source, migration, and toxicology of microplastic in soil. *Environmental International*, 137, p.105263.

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E. and Purnell, P., 2018. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal, and recycling. *Journal of Hazardous Materials*, 344, pp.179-199.

Hartline, N.L., Bruce, N.J., Karba, S.N., Ruff, E.O., Sonar, S.U. and Holden, P.A., 2016. Microfiber masses recovered from conventional machine washing of new or aged garments. *Environmental Science & Technology*, 50(21), pp.11532-11538.

Hayes, D., 2019. Biodegradable mulch performance and adoption in sustainable agriculture: A review. *Biodegradable Mulch Performance and Adoption*, 124, pp.1-6.

Hays, H. and Cormons, G., 1974. Plastic particles are found in tern pellets on coastal beaches and at factory sites. *Marine Pollution Bulletin*, 5, pp.44-46.

He, L., Wu, D., Rong, H.F., Li, M., Tong, M.P. and Kim, H., 2018. Influence of nano- and microplastic particles on the transport and deposition behaviors of bacteria in quartz sand. *Environmental Science and Technology*, 52, pp.11555-11563.

Hernandez, C.E. and Witter, S., 2016. Evaluating and managing the environmental impact of banana production in Costa Rica: A systems approach. *Ambio*, 25(3), pp.171-178.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C. and Thiel, M., 2012. Microplastics in the marine environment: A review of methods, occurrence, and effects. *Environmental Science & Technology*, 46, pp.3060-3075.

Huang, L., Wang, H., Wang, C., Zhao, J. and Zhang, B., 2017. Microwave-assisted surface modification for the separation of polycarbonate from polymethylmethacrylate and polyvinyl chloride waste plastics by flotation. *Waste Management & Research*, 35(3), pp.294-300.

Huerta Lwanga, E., Mendoza Vega, J., Ku Quej, V., Chi, J.L.A., Sanchez Del Cid, L., Chi, C., Escalona Segura, G., Gertsen, H., Salanki, T., van der Ploeg, M., Koelmans, A.A. and Geissen, V., 2017. Field evidence for transfer of plastic debris along a terrestrial food chain. *Scientific Reports*, 7, p.14071.

Hurley, R.R., Woodward, J.C. and Rothwell, J.J., 2007. Ingestion of microplastics by freshwater tubifex worms. *Environmental Science & Technology*, 51, pp.12844-12851.

Ibrahim, Y.S., Tuan Anuar, S., Azmi, A.A., Wan Mohd Khalik, W.M.A., Lehata, S., Hamzah, S.R., Ismail, D., Ma, Z.F., Dzulkarnaen, A., Zakaria, Z., Mustaffa, N., Tuan Sharif, S.E. and Lee, Y.Y., 2021. Detection of microplastics in human colectomy specimens. *JGH Open*, 5, pp.116-121.

Imhof, H.K., Sigl, R., Brauer, E., Feyl, S., Giesemann, P., Klink, S., Leupolz, K., Löder, M.G., Löschel, L.A., Missun, J. and Muszynski, S., 2017. Spatial and temporal variation of macro, meso, and microplastic abundance on a remote coral island of the Maldives, Indian Ocean. *Marine Pollution Bulletin*, 116(1-2), pp.340-347.

Ivleva, N.P., Wiesheu, A.C. and Niessner, R., 2017. Microplastics in aquatic environments. *Angewandte Chemie International Edition*, 56, pp.1720-1739.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M. Andrade, A., Narayan, R. and Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science*, 347, pp.768-771.

Jian, M., Zhang, Y., Yang, W., Zhou, L., Liu, S. and Xu, E.G., 2020. Occurrence and distribution of microplastic in China's largest freshwater lake system. *Chemosphere*, 261, p.128186.

Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M. and Klobučar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. *Environmental Pollution*, 250, pp.831-838.

Judy, J.D., Williams, M., Gregg, A., Oliver, D., Kumar, A., Kookana, R. and Kirby, J.K., 2019. Microplastics in soil: Microplastics in municipal mixed-waste organic outputs induce minimal short to long-term toxicity in key terrestrial biota. *Environmental Pollution*, 252, pp.522-531.

Khalid, N., Aqeel, M. and Noman, A., 2020. Microplastics could be a threat to plants in terrestrial systems directly or indirectly. *Environmental Pollution*, 267, p.115653.

Koelmans, A.A., Mohamed Nor, N.H., Hermsen, E., Kooi, M., Mintenig, S.M. and De France, J., 2019. Microplastics in fresh and drinking water: Critical review and assessment of data quality. *Water Research*, 155, pp.410-422.

Kole, P.J., Löhr, A.J., Van Belleghem, F. and Ragas, A., 2017. Wear and tear of tires: A stealthy source of microplastic in the environment. *International Journal of Environmental Research and Public Health*, 14(10), p.1265.

Kumar, M., Xiong, X., He, M., Tsang, D.C.W., Gupta, J. and Khan, E., 2020. Microplastics as pollutants in agricultural soils. *Environmental Pollution*, 265, p.114980.

Kumar, M., Xiong, X., He, M., Tsang, D.C.W., Gupta, J., Khan, E., Harrad, S., Hou, D., Ok, Y.S. and Bolan, N.S., 2020. Microplastics as pollutants in agricultural soils. *Environmental Pollution*, 265, p.114980.

Kumar, M.V. and Sheela, A.M., 2021. Effect of plastic film mulching on the distribution of plastic residues in agricultural fields. *Chemosphere*, 273, pp.128590.

Kumari, A., Rajput, V.D., Mandzhieva, S.S., Rajput, S., Minkina, T., Kaur, R., Sushkova, S., Kumari, P., Ranjan, A. and Kalinitchenko, V.P., 2022. Microplastic pollution: An emerging threat to terrestrial plants and insights into its remediation strategies. *Plants*, 11, p.340.

Laganà, P., Caruso, G., Corsi, I., Bergami, E., Venuti, V., Majolino, D., Ferla, R.L., Azzaro, M. and Cappello, S., 2018. Do plastics serve as a possible vector for the spread of antibiotic resistance? First insights from bacteria associated with a polystyrene piece from King George Island (Antarctica). *International Journal of Hygiene and Environmental Health*, 222, pp.89-100.

Lassen, C., Hansen, S.F., Magnusson, K., Hartmann, N.B., Rehne Jensen, P., Nielsen, T.G. and Brinch, A., 2015. Microplastics: Occurrence, effects, and sources of releases to the environment in Denmark. *Danish Environmental Protection Agency*, 1793, p.206.

Lei, L., Wu, S., Lu, S., Liu, M., Song, Y., Fu, Z., Shi, H., Raley-Susman, K.M. and He, D., 2018b. Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode Caenorhabditis elegans. *Science of the Total Environment*, 619, pp.1-8.

Li, J., Zhang, K. and Zhang, H., 2018. Adsorption of antibiotics on microplastics. *Environmental Pollution*, 237, pp.460-467.

Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X. and He, D., 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. *Environmental Pollution*, 242, pp.855-862.

Liu, M., Song, Y., Lu, S., Qiu, R., Hu, J., Li, X., Bigalke, M., Shi, H. and He, D., 2019. A method for extracting soil microplastics through the circulation of sodium bromide solutions. *Science of the Total Environment*, 691, pp.341-347.

Liu, Y., Zhang, J., Tang, Y., He, Y., Li, Y., You, J., Breider, F., Tao, S. and Liu, W., 2021. Effects of anthropogenic discharge and hydraulic deposition on the distribution and accumulation of microplastics in surface sediments of a typical seagoing river: The Haihe River. *Journal of Hazardous Materials*, 404, p.124180.

Lozano, Y.M. and Rillig, M.C., 2020. Effects of microplastic fibers and drought on plant communities. *Environmental Science & Technology*, 54, pp.6166-6173. https://doi.org/10.1021/acs.est.0c01051.

Luo, Y., Zhang, Y., Xu, Y., Guo, X. and Zhu, L., 2020. Distribution characteristics and mechanism of microplastics mediated by soil physicochemical properties. *Science of the Total Environment*, 726, p.138389.

Maaß, S., Daphi, D., Lehmann, A. and Rillig, M.C., 2017. Transport of microplastics by two collembolan species. *Environmental Pollution*, 225, pp.456-459.

Magnusson, K., Eliasson, K., Fråne, A., Haikonen, K., Hultén, J., Olshammar, M., Stadmark, J. and Voisin, A., 2016. *Swedish sources and pathways for microplastics to the marine environment*. IVL Svenska Miljöinstitutet

Mani, T., Frehland, S., Kalberer, A. and Burkhardt-Holm, P., 2019. Using castor oil to separate microplastics from four different environmental matrices. *Analytical Methods*, 11 (13), pp.1788-1794.

Marschner, B. and Kalbitz, K., 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma*, 113, pp.211-235.

Mintenig, S.M., Int-Veen, I., Loder, M.G.J., Primpke, S. and Gerdts, G., 2017. Identification of microplastic in effluents of wastewater treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water Research*, 108, pp.365-372.

Moller, J.N., Loder, M.G.J. and Laforsch, C., 2020. Finding microplastic in soils: A review of analytical methods. *Environmental Science & Technology*, 54, pp.2078-2090.

Napper, I.E. and Thompson, R.C., 2019. Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open air over a 3-year period. *Environmental Science & Technology*, 53, pp.4775-4783.

Naveed, M., Herath, L., Moldrup, P., Arthur, E., Nicolaisen, M., Norgaard, T., Ferre, T.P.A. and de Jonge, L.W., 2016. Spatial variability of microbial richness and diversity and relationships with soil organic carbon, texture, and structure across an agricultural field. *Applied Soil Ecology*, 103, pp.44-55.

Nizzetto, L., Futter, M. and Langaas, S., 2016. Are agricultural soils dumps for microplastics of urban origins? *Environmental Science & Technology*, 50, pp.10777-10779.

Panebianco, A., Nalbone, L., Giarratana, F. and Ziino, G., 2019. First discoveries of microplastics in terrestrial snails. *Science of the Total Environment*, 106722, pp.1-7.

Paul, A., Wander, L., Becker, R., Goedecke, C. and Braun, U., 2019. High-throughput NIR spectroscopic (NIRS) detection of microplastics in soil. *Environmental Science and Pollution Research International*, 26, pp.7364-7374.

Piehl, S., Leibner, A., Löder, M.G.J., Dris, R., Bogner, C. and Laforsch, C., 2018. Identification and quantification of macro-and microplastic on agricultural farmland. *Scientific Reports*, 8, p.17950.

Pignattelli, S., Broccoli, A. and Renzi, M., 2020. Physiological responses of garden cress (Lepidium sativum) to different types of microplastics. *Science of the Total Environment*, 727, p.138609.

Plastics Europe, 2018. *Plastics - The Facts 2018: An analysis of European plastic production, demand, and waste data for 2018*. EUA

PlasticsEurope, 2021. *Plastics - The Facts 2021: An analysis of European plastics production, demand and waste data*. Retrieved from: https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/.

Qi, Y., Yang, X., Pelaez, A.M., Lwanga, E.H., Beriot, N., Gertsen, H., Garbeva, P. and Geissen, V., 2018. Macro-and microplastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth. *Science of the Total Environment*, 645, pp.1048-1056.

Rezania, S., Park, J., Md Din, M.F., Mat Taib, S., Talaiekhozani, A., Kumar Yadav, K. and Kamyab, H., 2018. Microplastics pollution in different aquatic environments and biota: A review of recent studies. *Marine Pollution Bulletin*, 133, pp.191-208.

Rillig, M.C., 2018. Microplastics disguising as soil carbon storage. *Environmental Science & Technology*, 52, pp.6079-6080.

Rillig, M.C. and Bonkowski, M., 2018. Microplastic and soil protists: A call for research. *Environmental Pollution*, 241, pp.1128-1131.

Rillig, M.C., Ingraffia, R., de Souza, M. and Anderson, A., 2017. Microplastic incorporation into soil in agroecosystems. *Frontiers in Plant Science*, 8, pp.305719.

Rillig, M.C., Muller, L.A.H. and Lehmann, A., 2017. Soil aggregates as massively concurrent evolutionary incubators. *ISME Journal*, 11, pp.1943-1948.

Rocha-Santos, T. and Duarte, A.C., 2015. A critical overview of the analytical approaches to the occurrence, the fate, and the behavior of microplastics in the environment. *Trends in Analytical Chemistry*, 65, pp.47-53.

Rochman, C.M., 2018. Microplastic research: From sink to source. *Science*, 360, pp.28-29.

Rubol, S., Manzoni, S., Bellin, A. and Porporato, A., 2013. Modeling soil moisture and oxygen effects on soil biogeochemical cycles, including dissimilatory nitrate reduction to ammonium (DNRA). *Advances in Water Resources*, 62, pp.106-124.

Sarker, A., Deepo, D.M., Nandi, R., Rana, J., Islam, S., Rahman, S., Hossain, M.N., Islam, M.S., Baroi, A. and Kim, J.E., 2020. A review of microplastic pollution in the soil and terrestrial ecosystems: A global and Bangladesh perspective. *Science of the Total Environment*, 733, p.139296.

Scheurer, M. and Bigalke, M., 2018. Microplastics in Swiss floodplain soils. *Environmental Science & Technology*, 52, pp.3591-3598.

Schwabl, P., Koppel, S., Konigshofer, P., Bucsics, T., Trauner, M., Reiberger, T. and Liebmann, B., 2019. Detection of various microplastics in human stool: A prospective case series. *Annals of Internal Medicine*, 171, pp.453-457.

Silva, G., Madrid, F.G., Hernández, D., Pincheira, G., Peralta, A., Gavilán, M.U., Vergara-Carmona, V. and Fuentes-Peñailillo, F., 2021. Microplastics and their effect on horticultural crops: Food safety and plant stress. *Agronomy*, 11, pp.1528.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D. and Russell, A.E., 2004. Lost at sea: Where is all the plastic? *Science*, 304, pp.838.

Thompson, Richard C., 2015. Microplastics in the Marine Environment: Sources, Consequences, and Solutions. In: Bergmann, M., Gutow, L. and Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp.185-200.

Trasar-Cepeda, C., Leiros, M.C. and Gil-Sotres, F., 2008. Hydrolytic enzyme activities in agricultural and forest soils: Some implications for their use as indicators of soil quality. *Soil Biology and Biochemistry*, 40, pp.2146-2155.

Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M.B. and Janssen, C.R., 2015. Microplastics are taken up by mussels (Mytilus edulis) and lugworms (Arenicola marina) living in natural habitats. *Environmental Pollution*, 199, pp.10-17.

van den Berg, P., Huerta-Lwanga, E., Corradini, F. and Geissen, V., 2020. Sewage sludge application as a vehicle for microplastics in eastern Spanish agricultural soils. *Environmental Pollution*, 261, p.114198.

Veresoglou, S.D., Halley, J.M. and Rillig, M.C., 2015. Extinction risk of soil biota. *Nature Communications*, 6, p.8862.

Wan, Y., Wu, C., Xue, Q. and Hui, X., 2018. Effects of plastic contamination on water evaporation and desiccation cracking in soil. *Science of the Total Environment*, 654, 576-582.

Wang, F., Wong, C.S., Chen, D., Lu, X., Wang, F. and Zeng, E.Y., 2018. Interaction of toxic chemicals and microplastics: A critical review. *Water Research*, 139, pp.208-219.

Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G. and Zhang, H., 2019. Microplastics as contaminants in the environment: A review focusing on effects to organisms. *Science of the Total Environment*, 691, pp.848-857.

Wang, J., Taylor, A., Xu, C.Y., Schlenk, D. and Gan, J., 2018. Evaluation of different methods for assessing bioavailability of DDT residues during soil remediation. *Environmental Pollution*, 238, pp.462-470.

Weber, C.J. and Opp, C., 2020. An overview of the potential risks, sources, and analytical methods for microplastics in soil. *Environmental Pollution*, 267, p.115390.

Weithmann, N., Möller, J.N., Löder, M.G.J., Piehl, S., Laforsch, C. and Freitag, R., 2018. Organic fertilizer is a vehicle for the entry of microplastic into the environment. *Science Advances*, 4, p.8060.

Weithmann, N., Möller, U.N., Löder, M.G.J., Piehl, S., Laforsch, C. and Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment: A critical review. *Science Advances*, 4, eaap8060.

Xu, C., Zhang, B., Gu, C., Shen, C., Yin, S., Aamir, M. and Li, F., 2020. Are we underestimating the sources of microplastic pollution in terrestrial environments? *Journal of Hazardous Materials*, 400, p.123228.

Xu, C., Zhang, B., Gu, C., Shen, C., Yin, S., Aamir, M. and Li, F., 2020. Environmental impacts of microplastics: A critical review of the literature. *Journal of Hazardous Materials*, 400, p.123228.

Xu, G., Liu, Y. and Yu, Y., 2021. Effects of polystyrene microplastics on uptake and toxicity of phenanthrene in soybean. *Science of the Total Environment*, 783, 147016.

Yang, L., Zhang, Y., Kang, S., Wang, Z. and Wu, C., 2021. Microplastics in freshwater sediment: A review on methods, occurrence, and sources. *Science of the Total Environment*, 780, p.146546.

Yang, L., Zhang, Y., Kang, S., Wang, Z. and Wu, C., 2021. Corrigendum to Microplastics in soil: A review on methods, occurrence, sources, and potential risk. *Science of the Total Environment*, 780, pp.146546.

Zhang, G.S., Zhang, F.X. and Li, X.T., 2019. Effects of polyester microfibers on soil physical properties: Perception from a field and a pot experiment. *Science of the Total Environment*, 670, pp.1-7.

Zhang, S., Yang, X., Gertsen, H.N., Peters, P., Salánki, Y. and Geissen, V., 2018. A simple method for the extraction and identification of light-density microplastics from soil. *Science of the Total Environment*, 616-617, pp.1056-1065.

Zhao, S., Zhu, L., Gao, L. and Li, D., 2018. Limitations for microplastic quantification in the ocean and recommendations for improvement and standardization. *Marine Pollution Bulletin*, 127, pp.27-49.

Zhou, Q., Zhang, H., Fu, C., Zhou, Y., Dai, Z., Li, Y., Tu, C. and Luo, Y., 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and Yellow Sea. *Geoderma*, 322, pp.201-208.

Ziajahromi, S., Neale, P.A., Rintoul, L. and Leusch, F.D., 2017. Plastic pollutants in the water environment. *Water Research*, 112, pp.93-99.

Zubris, K.A.V. and Richards, B.K., 2005. Synthetic fibers as an indicator of land application of sludge. *Environmental Pollution*, 138(2), pp.201-211.