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Microplastics accumulation in agricultural soil: Evidence for the presence, potential effects, extraction, and current bioremediation approaches

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ABSTRACT

Decades ago, microplastic presence was corroborated in aquatic ecosystem, but revelations from current studies indicate microplastics (MPs) as ubiquitous environmental concern and demonstrate our plasticized life, because of microplastic existent in food, air, water, and soil. Existence of MPs in terrestrial ecosystem is long recognized now and additionally, all the evidence that has been found for microplastic entering the farm soils indicated that they are gradually accumulating in the agricultural soil. While previous studies focused extensively on marine systems, the increasing toxicity of MPs in agricultural cultivated soils and the aspects of MPs being accumulated causing bio-toxification are being looked upon presently. They potentially damage the yield of crop plants making their roots unable to uptake water and nutrients from the soil by accumulating near the roots. MPs have already invaded the terrestrial food chain and they have been detected in excreta of livestock animals along with earthworms and crop plants. MPs are abundant in farm soil that has interacted with sewage-sludge, plastic mulching sheets, organic fertilizers, and vermicompost for a long duration. This review focuses on current evidence of microplastic accumulation in farm soil, thereby enlightening the potential damages to crop plants, soil properties, soil microbes while ultimately reaching humans via the food chain. It also covers the recent advances for soil microplastic extraction, treatment, and possible bioremediation strategies.

1. INTRODUCTION

After the 1950's plastic production on commercial scale begun and after World War II new plastic production accelerated and gradually plastics became prominent [1]. Current plastic production globally is estimated to be 380 million tons per year risking the higher plastic pollution in environment. Microplastics (MPs) ranging below 5mm first came to notice in 1970s and are believed to cause the next possible global disaster if they keep accumulating in environment at this pace. MPs in aquatic ecosystem and their potential impacts on aquatic organism has been extensively studied but recently the accumulation of MPs in agricultural soil was detected however not much has been known until now. However, some investigations have exemplified the impacts of micro-nano plastics in the agroecosystem, yet only partial story is recognized in context with plants-soil-MPs interaction. Risks posed by micro and nano plastics are quite higher than their bulk counterparts in long run [2].

Plastics though being non-biodegradable, still get fragmented into smaller size plastics often referred to as micro or nano plastics in the environment. Not all types of plastics but the ones with low grades such as polyethylene, Polyvinyl, polystyrene, and polypropylene. can break down into smaller fragments when they are long exposed to external environmental conditions. Microplastic films or fragments have been profoundly detected in the agricultural land which generally includes polyethylene, polystyrene, polypropylene, low-density polyethylene [3]. In agriculture fields, plastic is often employed in mulching, plant seedling preparation, polyhouse or greenhouse areas and in vertical farming approaches [3]. Compost application in farmlands is again very common and beneficial practice that is being executed from early eras. Nonetheless, after the discovery of plastics and their widespread usage, the compost eventually started to have traces of plastics left, and upon using this compost for a longer duration can ultimately lead to microplastic accumulation in agricultural land. Sewage sludge and pig manure are other large rationale behind MPs accumulation followed by waste disposal [4,5]. Among all these sources sewage sludge application and plastic film mulching are considered the biggest reasons for microplastic accumulation and in comparison to non-plastic mulched soil the plastic mulched soils have more than twofold the amount of MPs and this is an indication to plastic contamination in soil as 128,000 Km^2 of worlds agricultural area has been mulched by plastic films till now [6].

Plastic mulching is apparently advantageous for crops as it acts as insulation film and raises crop yield, reduces weed growth, raises

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soil temperature, maintains sustainable water usage by crops through improving better water absorption and lower transpiration rates [7]. These are the reasons why plastic mulching is extensively employed in agricultural fields, especially in arid, semi-arid, and colder mountain regions [7]. The plastics eventually undergo weathering and keep accumulating in the soil hence polluting the soil with microplastic particles. In addition, the increment in number of landfill sites in recent years has made soil a large microplastic sink. Microplastic migration in soil occurs vertical and horizontal transportation i.e., they get transferred to humans and animals via terrestrial food chain horizontally and seeps down vertically into ground water with the run-off. The presence of MPs in sheep faces has also been detected which probably got biomagnified through feed and surrounding environment [8]. This review deliberates possible microplastic sources along with the corroborations from numerous studies conducted worldwide, followed by the toxic effects on living organisms and soil properties, extraction methodologies, and the current bioremediation techniques for cleaning the existing microplastic pollution.

2. EVIDENCE FOR OCCURRENCE OF MPs IN AGRICULTURAL SOIL

Evidence for the presence of MPs in terrestrial food chain was first detected in 2017 [15]. The study tested for the presence of MPs in garden organism and found good amounts of MPs in various samples of earthworm feces, chicken gizzard, and chicken feces had maximum concentration of 129.8 ± 82.3 particles g^{-1}. Here we discuss all the possible sources with evidences from different studies, contributing to soil microplastic accumulation.

2.1. Sewage Sludge and Vermicompost

Sewage treatment units remove MPs from the wastewater to purify it thereby accumulating the MPs in the sewage sludge. Sewage sludge is being sustainably utilized for fertilizing the farmlands and this constant application as fertilizer has indirectly led to the incorporation of micro and nano plastics in agricultural soil [17]. Compost application on fam soil also evidently leads to microplastic incorporation [14]. A study tested for microbial activity in soils treated with MPs (mainly Polypropylene and Low-Density Polyethylene), the consequences were lower microbial biomass in the soil with these MPs [11]. Higher microplastic particles and fragments per kilogram per hectare of soil were found in a study [3].

2.2. Plastic Mulching as an Evident Microplastic Source

Plastic mulching is quite common practice in fields that cultivate, so the fields that have been mulched for years long are very prone to microplastic accumulation [18]. Although further analysis is required to know if it enters the vegetables, however by testing sheep feces it is moderately clear that microplastic particles can be transferred from soil to the feeds of the animals. Consequently, this is possible that they might be entering the vegetables and then ultimately to humans. Fibers, microbeads, polyamides were majorly detected in a study conducted in vegetable farms [12]. Soils with different characteristics and type accompanied with higher exposure time to inorganic fertilizers collectively determine the effect of MPs on the soil [13]. Different types of soil and cropping patterns affect the role of MPs in changing pH or microbiota of the soil. Lagooning sludge with green waste was studied by co-composting in three separate batches and the amount of MPs varied with the amount of sludge mixed, this indicates that higher sludge application leads to higher microplastic accretion in soil [16].

2.3. Irrigation Methods, Flooding, and Run-off

The presence of MPs in water bodies is long known now and in certain areas irrigation or flooding and run-off transfer these aquatic MPs to the agricultural fields. Crop fields that are near water resources are more predisposed to this, while irrigation from rivers, groundwater, lakes that already have microplastic occurrence causes soils to contaminate too [6]. Flooding is another major cause because floods can sweep huge amounts of garbage and waste along with them from water bodies and even waste from landfill sites to the agricultural land [19].

2.4. Plastic Waste Disposal, Littering, Industrial Wastes

Landfilling is an unsustainable but unavoidable waste management choice which is practiced by municipalities, industries, and ordinary citizens for disposing off city waste, industrial effluents, and domestic waste respectively. Even though it is retentive process, ultimately the plastic waste keeps breaking into smaller particles due to environmental conditions and get run-off with wind or heavy rains to nearby crop fields [12,20]. The plastic waste from these landfill sites also release leachates, toxic chemicals, and heavy metals that increase soil pH and soil toxicity [21]. Table 1 shows evident sources and types of MPs detected in farm soil and techniques used to identify and quantitate them.

3. POTENTIAL EFFECTS OF MPs

Soil MPs have been found to pose adverse impacts on soil properties, soil organisms such as earthworms, nematodes, fungi, microbial biota, fungi, bacteria, chicken, and pig. Furthermore, several evidences have indicated microplastic uptake by crop plants and then accumulating through levels of the food chain causing expected toxicity in humans and larger animals.

3.1. Potential Effects on Soil Texture and Properties

Soil MPs have major effect on the soil pH accompanied by increment in plant and human pathogens in the soil [13]. MPs profoundly deteriorate the soil heath gradually. A study conducted in a home garden showed the entry of MPs into the terrestrial food chain via soil and the presence of MPs in high concentrations was detected in the fecal matter of earthworms, chickens and in the crops too [15]. Microplastic presences in soil deteriorate biophysical properties of soil, i.e., disturbing water-soil interaction, causing leaching, soil-microbe interactions. MPs are believed to increase the soil bulk density, disturb soil hydrological properties and physicochemical characteristics, which can implicate to difficulty in rooting of plants [22,23]. Apparent neurotoxicity and higher oxidative stress were observed in earthworms in the MP containing vermicompost furthermore MPs negatively impacting the pH, C/N ratio of soil [24]. MPs percolating in soil comes with heavy metals such as Pd, As, Cu, and Co., and organic pollutants in the polluted soil [10], but research on MPs in relevance with heavy metal toxicity is very partial and therefore, requires further exploration. Moreover, MPs can alter carbon cycling in soil by changing decomposition process and also interfere in SOC (soil organic carbon) determination for soil quality checking [25,26]. Higher cadmium mobility was seen as threat in microplastic polluted soil [2].

3.2. MPs Effects on Plants and Food Crops

Several studies on the interaction between soil MPs and plants have shown the negative effects of MPs as shown in Figure 1. A clear uptake by roots and localization of MPs occurs in plants via Apo-plastic pathway as demonstrated by employing fluorescent MP particles [27],

Table 1: Various research evidence for microplastics incidence in farmland.

Source	Experimental method	Detection technique	Observations	References
Manure application in soil	Swine-poultry manure and soil testing	FTIR spectroscopy	Fragment and fibers of PP and PE	[9]
Sewage sludge-based fertilizers	Soil testing	μ-FTIR	Earthworms were found in very low numbers	[5]
E-waste disposal site	33 soil samples form 10 different plots	FTIR spectroscopy	60 types of microplastics with different colors were detected along with heavy metals	[10]
PP and LDPE in organic soil	Microbial activity determination	DOC-DON ratios	Reduction in microbial biomass	[11]
Plastic mulching in cropland with vegetables	Sheep faeces and soil testing	Stereomicroscope	Presence of microplastics	[8]
Domestic garbage	Replicates of soil testing	Stereomicroscope and anatomical needle	Presence of both MPs and polymers (fibers, beads, polyamides)	[12]
Long term inorganic fertilizer application	9 soil samples for different types of soil	TOC analyzer, QIIME, FAPROTAX database, HT-qPCR	Changes in soil pH and soi microbiota	[13]
Compost application	Horticultural and agricultural soil sampling	Density separation and light microscopy	Presence of MPs	[14]
Plastic waste	Chicken faeces, earthworm cast, crops, soil testing	Stereomicroscope and statistics	Evident transfer of MPs to food chain	[15]
Agricultural plastics	Soil sampling	ATR-FTIR spectroscopy	Several plastic polymers detected	[3]
Lagooning sludge	Microplastic testing in co-compost, dewatered/dry sludge, and fresh sludge	GC-MS; fluorescence staining microscopy; Raman spectroscopy	Varied amounts of microplastics detected	[16]

FTIR: Fourier transform infrared spectroscopy, TOC: Total organic carbon, QIIME: Quantitative insights into microbial ecology software, HT qPCR: High throughput analysis quantitative polymerase chain reaction, DOC: Dissolved organic carbon, DON: Dissolved organic nitrogen, GC-MS: Gas chromatography-mass spectrometry

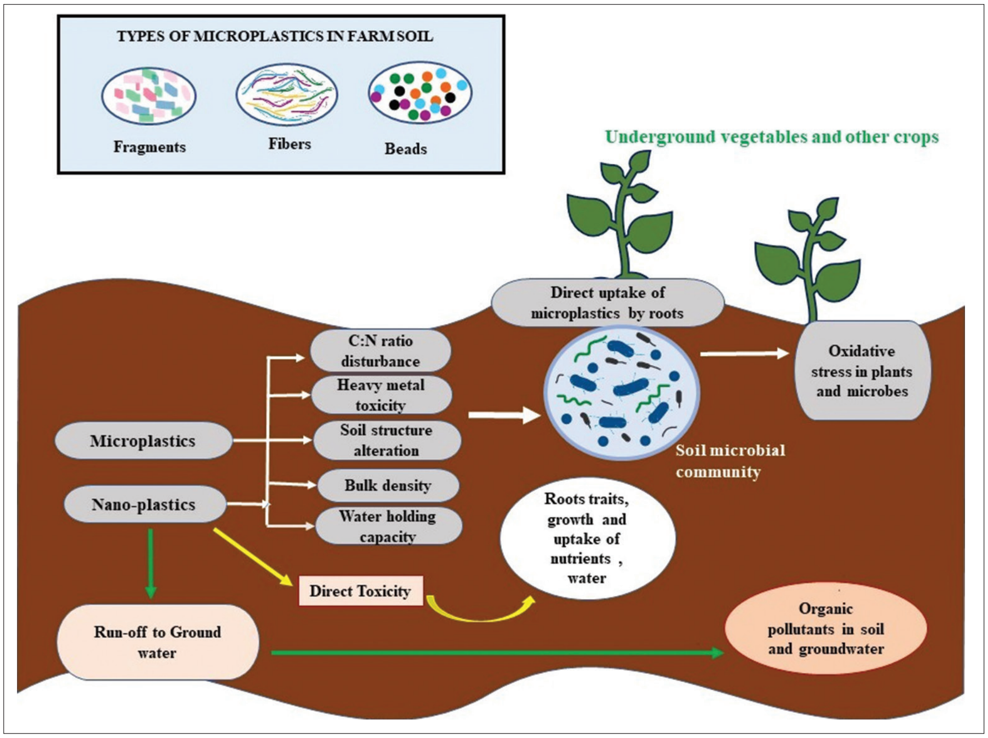

Figure 1: Conceptual diagrammatic representation of possible effects of microplastics on plant growth and soil properties.

also MPs cause blocking of intercellular connections in roots thereby lowering the nutrient transfer and decreased biomass, lower catalase activation in higher plants and declined growth at higher microplastic concentrations [28].

The accumulation of nano plastics in *Arabidopsis thaliana* plant was demonstrated in a study thereby also revealing the uptake of both negative and positively charged MPs giving a direct proof for internalization of micro-nano plastics in plants via the roots [29]. Higher arsenic concentration was detected in rice seedlings under exogenous microplastic presence leading to a higher reactive oxygen species (ROS) and lower Rubisco function and production thereby disturbing the normal photosynthesis process [30]. They are also found to be inhibiting uptake of nutrients via roots of rice plants thereby lowering biomass and yield decrement [30]. Polyethylene MPs in soil cause lower metal ion (Pb and Zn) adsorption thereby lowering the metal bioavailability [31].

In addition to changing the soil properties such as pH and causing soil acidification, low-density polyethylene and biodegradable plastic mulching film accumulation in soil causes disturbances in wheat rhizosphere thereby disturbing their structure and strongly effecting wheat growth [32]. Significant decrement in mineral levels of Mg, Ca, and Fe alongside metabolite production was detected in cucumber fruits in presence of Polystyrene nano plastics and these nano plastic particles were absorbed via roots and after accumulation in root, they were distributed across leaves and fruits [33]. These non-biodegradable microplastic fragments in agricultural soil apparently take hundreds to thousands of years to mineralize [34].

Microplastic pollution in soil adversely effects photosynthesis as observed in Lettuce plants that showed a reduced superoxide dismutase activity and dysregulated photosynthetic activity and electron transfer hurdles induced by two types of polyvinyl chloride (PVC) MPs PVC-a and PVC-b [35]. MPs cause delay in seed germination and slower root growth as they accumulate at the germinal pore of seeds acting as physical blockers [36]. Soil being porous in nature allows MPs to migrate to deeper soil layers via run-off and this can highly effect root growth, water absorption efficiency, and root movement [37], mentioned in Table 2.

3.3. Conceivable Effects on Human Health

Raman spectroscopy analysis indicated exogenous accumulation and uptake of MPs by root vegetables such as radish has increased the concern of microplastic ingestion through food and higher amount of MPs reaching humans and is a threat to food safety and health concerns [43]. It has been revealed that MPs in aquatic animals lead to neurotoxicity in the brain so it might be possible that similar impacts can be observed in human brains [44]. Several evidences indicate MPs reaching humans through inhalation, physical contact or ingestion and further circulated to different vital organs trailed by harmful consequences of MPs on human health which comprises respiratory, digestive, the circulatory system of the body, wherein major effects include oxidative stress, inflammation, lowering cell viability, changes in cellular morphology, reduced gene expression, lesions in organs, immune disorders and neurotoxicity [45].

3.4. Effect of MPs on Soil Microbes and Soil Organisms

Microbe movement in soil is influenced by the soil's characteristics and nutrient availability [46]. MPs have been demonstrated to affect soil organisms in numerous studies. Nematodes, Lepidopteran larvae, Soil microarthropods, Ants, Oribatid mites, and Dipteran larvae will all have smaller populations as a result of microplastic in the soil since the ingestion of tiny microplastic pieces by these soil organisms causes intestinal injury and oxidative damage [42]. Plastic mulch applied in agricultural soil can be broken down into fragments by soil microbes and these two, plastic mulch and soil microbes came in contact just after the process of mulch installation [47]. The activity of enzymes is being negatively affected by the different shapes of the MPs. Fibers and foams shape of microplastic negatively impacts the enzyme N-acetyl β- glycosaminidase and cellobiosidase activity. Fibers show negative effects by stopping the development of macroaggregates and forms that could be related to the adsorption process of microplastic. Both shapes result in the reduction of the enzyme activity by combating the oxygen diffusion and by affecting water flows in soil pores [39]. Plastic films also have a negative effect on the activities of enzymes that could be the result of increased evaporation of soil water due to the presence of MPs [41].

MPs seem to have enhanced outcomes on certain bacterial communities. *Bacteroidetes*, *Acidobacteria*, and *Chloroflexi* are among the microbial communities that live on the surface of MPs with flakes and pits by establishing colonies on the surface of microplastic and have different sizes and structures from those found in soil and plant litter. These microbial populations aid in the biodegradation of MPs, and "special microbial accumulators" are MPs that contain these microbial communities [48]. MPs made of polypropylene and low-density polyethylene have little influence on the soil microbial community and the activities of soil microbes and mineralization of Nitrogen, nitrification, and soil respiration were not affected by the addition of MPs [11]. The exact mechanism behind bacteria forming

Table 2: Types of microplastics in soil with examples and effects.

Microplastic type	Hypothesized effect on soil	Potential effect and concern for crop plants	Examples of microplastic	References
Fiber	Alterations in soil structure	Not known clearly	PE, PP, PS	[22,38,39]
Film	Higher evaporation of water from soil	Lower water availability for crops leading to slow growth	PP, PE, LDPE	[40,41]
Bead/Microbead	Soil texture variations	Uptake by roots, less effects	PP, PVC, PE, PS	[22,27]
Fragment	Changes in properties of soil	Unclear effects	PP, PS, LDPE	[39,42]
Nanoplastics	Toxic to roots of plants and microbes	Underground edible plant parts (higher plastic ingestion)	PSNP	[29,33]

PE: Polyethylene, PP: Polypropylene, PS: Polystyrene, LDPE: Low density polyethene, PVC: Polyvinyl chloride, PSNP: Polystyrene nanoparticles biofilms over plastic surface is not known, however, bacteria have this great strategy to survive in unfavorable conditions by producing metabolites that can potentially degrade MP fragments [49].

4. EXTRACTION AND IDENTIFICATION OF MPs FROM FARM SOIL AND QUANTIFICATION

A major impediment for studying and identifying micro-nano plastics is the absence of a standardized protocol for their extraction and successful identification from the farm soil. The protocol as demonstrated in Figure 2, involves multiple steps starting from soil sample collection, and eventually the identification of types of MPs. Even if it is laborious, it is quite efficient. Studies focusing on extraction and analysis of agricultural soil MPs employ advanced microscopic techniques such as Confocal and Stereomicroscopy, Fourier transform infrared (FTIR) spectroscopy, mass spectroscopy, fluorescence labeling, Raman spectroscopy, statistic stools such as analysis of variance, for identification, characterization of the extracted micro and nano-plastics.

4.1. Sample Collection

Soil sample collection is vividly dependent upon the non-uniform presence of MPs in soils, and it can be taken from single or composite sites. But due to this non-uniformity, it is preferable to perform the composite sampling approach, which entails collecting soil from various sites within the same sampling region, mixing it thoroughly, and merging it into a single sample [50]. The stainless-steel instrument shovel can be used to gather soil samples with sampling units of 5×5 cm and 10 × 10 cm or cotton cloth can be used to prevent external contamination [51]. The soil sample is covered with aluminum foil, then kept in a sampling bag and taken back to the laboratory. The collected sample must be kept in a neat and clean place with proper lighting and a very low temperature [52].

4.2. Analysis of Sample

The procedure for the analysis of microplastics in the soil includes three major steps wherein, the first step follows the process of drying and sieving the soil samples followed by the second process where removal of the organic waste from the microplastic particles is done. Now in the third process using the density separation microplastic particles are separated. Then finally characterization of microplastics is being done by using a microscope [50].

4.2.1. Drying

4°C temperature is recommended for the storage of soil samples. Even though samples should be dried in the natural air, or oven can be preferred for faster and easier drying of the samples. Here, sudden high temperature exposure in the oven can affect the microplastic structure so for such MPs, heating temperature can be reduced up to 50°C [53].

4.2.2. Sieving

The separation of microplastic from a dried soil sample is being done by using sieves of variable pore size. In general, sieves with variable pore sizes 1 mm, 2 mm, and 5 mm have been used. By using different pore sizes, we can separate different types of MPs and during sieving the MPs remain in the sieve while other material passes through the sieve [54].

4.2.3. Purification

Organic fibers and organic matter due to their similar density may conceivably cause disturbance in MPs analysis. We must remove all these from the soil sample by chemical digestion. In most of the studies oxidant digestion, strong acid digestion, and alkali solution digestion were used. We can use HNO_3 digestion but as it is a strong acid, can cause denaturation of microplastic. So instead of HNO_3, it is better to use 30% H_2O_2 or Fenton's reagent for the removal of organic matter [6,53].

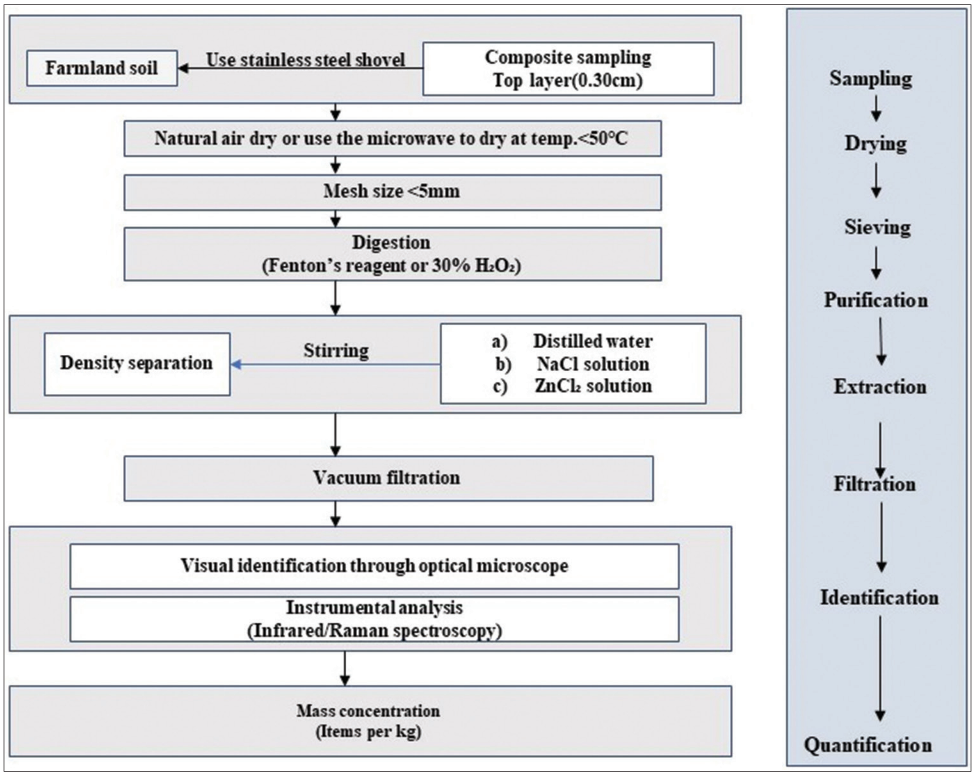

Figure 2: Sampling, extraction, and analysis procedures for microplastics in soil.

4.2.4. Extraction

Further to extract the MPs from the purified soil samples involves density-based and non-density-based approaches and the latter is comparatively inexpensive and unsophisticated. For density-based extraction certain solution are used and the solutions that are used for the microplastic extraction are distilled water, sodium chloride, zinc chloride, calcium chloride, and sodium iodide with density 1.0 g/cm^3, 1.2 g/cm^3, 1.6 g/cm^3, 1.5 g/cm^3, 1.8 g/cm^3 respectively. The simplest method among them is to use distilled water, which can separate only those MPs having a density <1.0 g/cm^3. Also, NaCl can extract only low-density microplastic although it is cheap, accessible, and safe to use [55]. For microplastic having higher density we can use $ZnCl_2$ solution, its disadvantage is that it is toxic and burning in nature. The most expensive solution is NaI with high density. $CaCl_2$ is the best solution in every possible way for the separation of microplastic [56].

In case of high-density polymers, the density approach fails except for NaBr solution and thus non-density approach seems to be promising in such conditions. In non-density-based approach [51] used olive oil for microplastic extraction by exploiting olive oil's affinity for wide variety of high-density polymers (HDP) and this method had a recovery rate of above 90%. Non-density-based approach does not require salt solutions but essentially consists of freezing step to prevent oil mixing with samples which prevent obstacles during FTIR or Raman spectroscopic analysis.

4.2.5. Filtration

In this process, MPs get separated from the supernatant. The filter membranes that have been most used are glass fiber, polytetrafluoroethylene (PTFE), quartz, and nylon. Quartz and glass fiber membranes were not proved much helpful since they release a lot of fibers in the deionized water and cause disturbance in the analysis of MPs. Nylon membrane and PTFE have no such problem. Lastly nylon, membranes were in more use as PTFE has difficulty in water filtration due to the hydrophobic nature of the membrane [57].

4.3. Identification and Quantification

4.3.1. Visual identification and detection of MPs

In the initial period, the light microscope was in use for the visual identification of microplastic, but it has a lot of inaccuracies in the results. "Hot needle test" was also employed in various studies to distinguish plastic from natural particles. Later, this method was used for the identification of low-density polymer by taking their initial microscope picture and picture after the sample was heated at a temperature of 130°C. Those particles which are melted are considered thermoplastic polymers. Although this cannot help in HDP identification [58].

FTIR and Raman spectroscopy can also be used for the identification of MPs, where FTIR can analyze particles having a size >500 mm but with a disadvantage that it is unable to analyze wet samples and requires completely dried samples [9]. Also, irregularly shaped MPs perhaps generate extra noise and unexplained spectra. Raman spectroscopy can analyze the MPs which have a size >1 µm, it has high-resolution power and can analyze wet samples efficiently [16,50]. MALDI-TOF MS is another approach that uses charge to mass ratio for ionizing and detecting environmental pollutants including MPs which starts with initial ionization via vaporized matrix followed by TOF and separation based on mass to charge ratio and concluded by MS results [59]. This method has been found to be effective for long weathered and both low and high-density microplastic samples.

4.3.2. Quantification

In the soil studies, the process of quantification for the MPs involves Counting, Weighing, Mathematical calculation, and Instrumental analysis. The counting method has unit N/kg or N/m² and it is more in use. When weighing being compared with the previous one, it would be easier to use, and the unit of weighing is mg/kg. For those soil samples which have high microplastic concentration, the weighing method would be better for their quantification. In studies, the relationship found between the microplastic's weight and particle volume is taken after heating is linear. Using instruments such as TGA-MS the concentration of microplastic directly can be measured. The extraction step is not required in the case of direct quantification but we are unable to determine the shape, size, and color of the MPs [60].

5. CURRENT RESEARCH AND POSSIBLE APPROACHES TOWARDS BIOREMEDIATION AND PREVENTION OF MICROPLASTIC ACCUMULATION IN AGRICULTURAL SOIL

As we know, the probable microplastic pollution sources are known that majorly include – plastic mulching, pig manure, garbage disposal, landfill sites, vermicompost, sewage sludge application to agricultural soil. So, we can aim at preventing the initial removal of MPs from these sources before applying them to the crop fields. Besides this, another approach can be focusing entirely on the already contaminated crop fields and this can be done via phytoremediation approaches that include phytoextraction and Phyto-filtration to remove soil micro-nano plastics [61].

5.1. Biodegradable Plastic Mulching Instead of Traditional Mulching

To remediate MPs from soil we need to eliminate plastics from the source itself because removing MPs from large farm area is comparatively difficult. In place of plastic mulching, which is usually made of PE, the use of biodegradable plastic mulching can be preferred. Biodegradable plastic mulching is being used but it has certain additives that are left behind even after degradation like carbon black or polyethylene, which on long term application gets accumulated as toxics in the soil resulting in higher carbon content in soil [4].

MPs being the emerging farm soil pollutant makes it important to degrade them either within the MPs source or to deal with the microplastic polluted agricultural soil. But the later seems quite complex considering the larger farm area. So, several conducts can be implicated to biodegrade the plastics in their possible sources. The degradation approach should be biodegradable and in eco-friendly manner, i.e., by using bacteria, fungi, algae, or microbial enzymes.

5.2. Bacterial Degradation of MPs

Soil MPs can be removed with the help of bacteria and two strains of bacteria *Bacillus* were used in the biodegradation of MPs which are *Bacillus gottheilii* and *Bacillus cereus* [62]. In the studies, it has been found that these microbes produce certain enzymes that successfully degrade polyethene and the enzyme released were esterase and laccase which have the alkane hydroxylase producing gene which is responsible for the degradation of LDPE [63]. In another study, initially, UV treatment was done on bacteria *Bacillus subtilis* and then some biosurfactant was added. Both strengthened the microbial potential for microplastic biodegradation. Since biosurfactants are amphiphilic they aid microbes in attaching to the surface of MPs because MPs lack an affinity for water [64]. No wonder that

Pseudomonas is the common genus of bacteria when it comes to polymer degradation, as studies have shown that bacteria's capacity to dissolve plastic is based on their innate ability to digest fatty acids. Because it improves colony adhesion and persistence, biofilm growth has been demonstrated a major role in the degradation of MPs. Because of their homopolymeric makeup, thermoplastics are more resistant to microbial biodegradation. One of the most noteworthy findings on plastic degradation is the potential of *Ideonella sakaiensis*, a unique species which is isolated from a consortia of garbage dump bacteria to digest polyester as its primary source of energy and carbon. Some bacterial species have been demonstrated to degrade polystyrene and polycarbonate. *Bacillus, Pseudomonas*, and *Micrococcus*, for instance, have been shown to degrade a variety of thermoset polymers, primarily polyurethane [65,66].

5.3. Fungal Degradation of MPs

The potential of various fungus species to degrade various plastic polymers has been highlighted based on their ability to use polymers of these MPs as their primary source of carbon or energy. A wide range of fungal strains from various classes has been found to degrade plastics in this regard. According to recent studies, the *Aspergillus* genus has been found the most important fungus for the biodegradation of manmade plastics. Three *Aspergillus* species, *Aspergillus clavatus*, *Aspergillus fumigatus*, and *Aspergillus niger*, have been found to degrade Polyethylene, Polyurethane, and Polypropylene, respectively which are isolated from various terrestrial habitats. *Aspergillus oryzae* strain A5 is found to play an important role in the bioremediation of microplastic such as polyethylene. Fungal enzymes, particularly depolymerases, have a wide specificity that allows them to break down a variety of polymers [67]. Fungal hyphae's dispersion and penetrative ability, as well as their ability to release hydrophobins for improved hyphal adhesion to hydrophobic surfaces, have been recognized to be important factors in their initial colonization before eventual depolymerization. Pretreatment of diverse substrates involving numerous parameters such as photo-treatment and temperature, acid pretreatment, and various additives has indicated the improvement of fungal biodegradation of plastics [66].

5.4. Enzymatic Plastic Biodegradation

Several extracellular and intracellular microbial and de novo synthesized enzymes have been discovered that are involved in the biological degradation of polymers. Major enzymes being hydrolytic in nature includes cutinases, lipase, protease, esterase, laccases, peroxidase, etc. Extracellular enzymes have been studied widely and have a wide spectrum of reactivity, ranging from oxidative to hydrolytic functionality which involves in the depolymerization of long carbon chains in polymeric polymers to oligomers, dimers, and occasionally monomers [68]. Intracellular enzymes are less efficient, but the extracellular enzymes are engaged in chemical reactions at the solid/liquid boundary, as they act on macromolecules present on the solid plastic's surface. The resulting surface functionalization of hydrophobic plastic surfaces leads to the breakdown of plastic metabolic intermediates into monomeric units, and the final mineralization of the final monomeric intermediates is all mediated by different enzyme groups. While the aerobic and anaerobic processes required to convert intermediates to molecules that may be ingested by bacteria are carried out by a huge number of intracellular enzymes [62,65].

Several microbes have shown the ability to successfully biodegrade varieties of plastics like polyethylene, polyethylene terephthalate, polylactic acid, and other aliphatic plastics. These plastic degrading microbes as mentioned in Table 3 majorly constitute bacteria, fungi isolated from soil, marine environment, plastic waste dumping sites, and some from the gut of super worms [69-72].

Table 3: Several isolated microbes and their plastic degrading enzymes.

S. No.	Enzyme responsible of biodegradation	Source	Type of plastic	Reference
1.	Cutinase	*Thermobifida alba* AHK119	Modified polyethylene terephthalate	[70]
2.	PETase and MHETase	*Ideonella sakaiensis*	PET	[69]
3.	Protease, Lipase	*Pseudomonas mendocina* and *Actinomucor elegans*	Polylactic lactic acid Polybutylene adipate terephthalate	[72]
4.	Hydrolytic enzymes	*Amycolatopsis*	PLA	[73]
5.	-	*Pseudomonas* sp.	Polyphenylene beads	[71]

6. CONCLUSION AND FUTURE PERSPECTIVES

Knowledge gaps remain prominent for microplastic accumulation in agricultural soil, subsequently, there is a need of further research to determine effects and degradation of plastics in livestock guts and potential effects on their health via the plant feed or their environment. Currently, no precise and standardized solution is available for microplastic remediation and preventing it to reach plants, livestock and ultimately humans causing biomagnification. Although microplastic degradation within the appears a better option than the degradation in farm soil but the damage that has been already made needs repair and repenting. Vast studies are required which would implicate toward developing standardized strategies for eco-friendly microplastic remediation.

Biodegradable plastic mulching sheets are perceived as an alternative to traditional plastics, nonetheless, it also leaves behind additives even after degradation also the other bioremediating methods includes microbes, majorly bacterial species, and microbial enzymes. Additionally, proper studies are required to determine the hypothesized effects of MPs on the crops and plant growth and nutrient mobility. Globally few studies have been done on impact of MPs on soil and plants but in consideration with global scenario further interdisciplinary and comprehensive research is required to assess the effects of plastic residue complex. Likewise, the current methods employed for microplastic extraction, isolation, and examination are quite laborious and time taking, so there is a need to develop consistent protocols. Metagenomic approaches can help in identifying novel plastic degrading microbes, gene structures, and enzymes responsible for plastic degradation by using high throughput screening and next generation sequencing technology and analogous computational biology methods [74].

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8. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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10. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

11. ETHICAL APPROVALS

Not applicable.

12. DATA AVAILABILITY

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

13. PUBLISHER'S NOTE

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