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Review article

Micro and nanoplastics ravaging our agroecosystem: A review of occurrence, fate, ecological impacts, detection, remediation, and prospects

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ABSTRACT

Micro-and nanoplastics (MNPs) are particles that are smaller than a millimeter in size and have infiltrated both terrestrial and aquatic ecosystems. MNPs pollution have become a widespread problem causing severe adverse effects on human health and the environment worldwide. Once in the environment, these polymers are not easily degradable due to their recalcitrant nature and small size and are easily consumed by aquatic organisms and transported through the food chain, at great risk to human health. Substantial evidence demonstrates the negative effects of MNPs residues on aquatic organisms' reproductive and developmental defects. Similarly, soil flora, soil quality, and plant height have been severely impacted by their presence in the agroecosystem. This is evident in the inhibition of water absorption by blocked seed pores, delayed germination, and the dramatic decline in transpiration rates and growth of plant roots, inevitably leading to drop in biomass and crop production, posing an overall threat to global food security. In this review, we present the impact of MNPs in agroecosystems around the globe, including their sources, occurrence, distribution, transport, and ultimate fate. We recommend using bio-based

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plastics, eco-friendly remediation strategies, reformed agricultural practices, non-single-use synthetic plastic legislation, and increased plastic waste disposal awareness campaigns as effective tools to mitigate this problem.

1. Introduction

Micro-and nanoplastics (MNPs) pollution is becoming more prevalent around the world. They have a diameter of fewer than 5 m, are made up of various chemical constituents, and can be found in environmental compartments [1]. Ecosystems receive plastic pollution in 1.15–2.41 million tonnes per year [2,3]. The degradation, weathering or expsore of plastic frgaments to ultraviolet light results to the formation of MPs and NPs [4–6]. MPs are little plastics of less than 5 mm in diameter that are extremely persistent and pervasive in various environmental matrices [7]. Primary and secondary MPs are the two categories of MPs. For specific uses, like as abrasives in toothpaste, shaving cream, and similar goods, primary MPs are produced in small sizes. On the other hand, secondary MPs are thought to be the result of the degradation and improper management of macroplastics, such as different kinds of plastic bottles, fishing nets, plastic bags, and waste plastics [6]. Polymers that are less than a micron in size are referred to as NPs. NPs are described as being either 100 nm or 1000 nm in size in one dimension, while the scientific definition is still debatable [4,8]. MNPs have several elemental constituents, such as composite chemicals, small sizes, sheer volume, ubiquity, and burgeoning anthropogenic activities that significantly impact ecosystems. Their impact on the ecosystem could be direct on food production or indirect on plant growth and development, microbial decomposer, nutrient cycling, attachment for multiplying organisms, organisms' digestive/root systems, and vectors of toxic compounds [7,9–11].

MNPs have endangered ecosystem sustainability and have become a global concern for human exposure because MNPs particles tend to bioaccumulate and biomagnify through the food chain [12]. They are small enough to be consumed by a wide range of

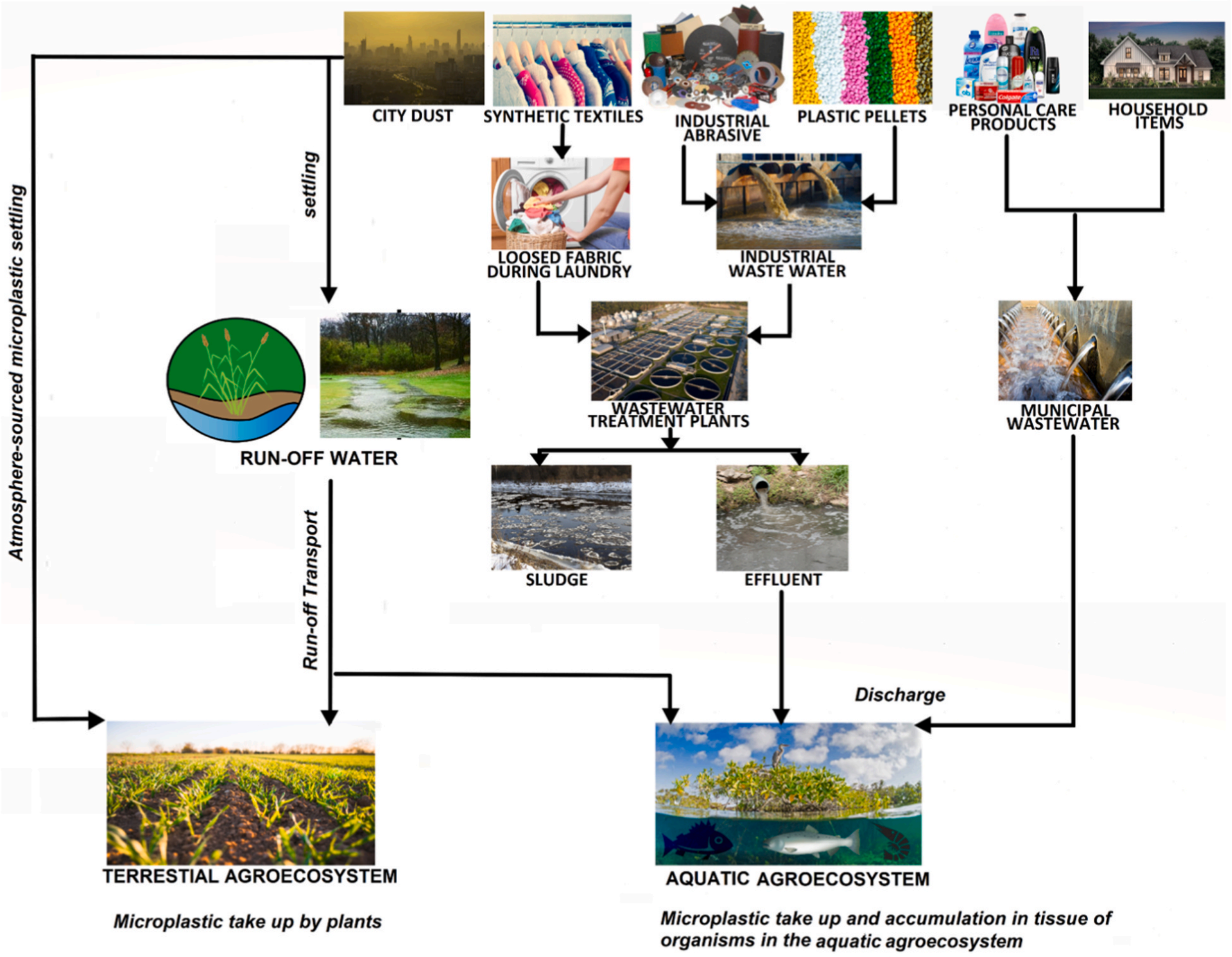

Fig. 1. Sources of MNPs in agroecosystems. MNPs from primary and secondary sources reach the agroecosystem directly and indirectly.

organisms, and they may be able to cross biological barriers at the nanoscale. MPs can influence a variety of essential soil biogeochemical processes by causing numerous effects on microbial activities and functions, establishing specific microbial hotspots, and altering the characteristics of the soil. The direct toxicity of MNPs or the indirect alteration in soil physical structures and microbial populations can explain the mixed effects of MNPs on plant development and performance [13,14]. However, knowledge of their ecological impact on agroecosystems is limited. Due to the high inputs of some recycled organic waste, plastic film mulching, and plastic particle loading in agroecosystems, it is critical to understand more about any potentially harmful or adverse effects of these pollutants on agroecosystems [1].

Besides, addressing the research gaps in the knowledge of microplastics (MPs) and nanoplastics (NPs) in agroecosystems could adequately protect the world food supply, based on the limited findings and understanding that the shortfall of information of ecological impact from MNPs in agroecosystems does not correspond with the absence of evidence [14]. This study, therefore, scrutinized the global literature on the ecological impacts of MNPs in agroecosystems by elucidating the sources of MNPs in agroecosystems, occurrence, fate, ecological risks, and bioavailability of MNPs, impacts, uptake and accumulation of MNPs in plants, and responses of aquatic organisms to MNPs in agroecosystems. In addition, this review suggested possible remediation and management approaches for regulating MNPs surge in agroecosystems.

2. Major sources and occurrence of micro-and nanoplastics as emerging pollutants in the soil and agroecosystem

MNPs are a terrific nuisance causing severe adverse effects to human health, soil ecology, and the environment in general. Numerous studies have thoroughly investigated their impact on aquatic ecosystems (water bodies and oceans) [15,16]. However, there are still a lot of gaps in knowledge of their impact on soil, terrestrial, and agroecosystems [17]. Several thousand to millions of tons of plastics are globally produced, and their applications are diverse in supporting livelihoods. According to the statistics published by Plastics-Europe and the European Association of Plastics Recycling and Recovery Organization (EPRO), global plastic production as of 2016 was estimated to be around 335 million tons, with an average growth rate of 8.6% annually since the 1950s [18]. Supporting evidence has shown that these plastics form major sources of recalcitrant MNPs in the agroecosystem (Fig. 1). Ng et al. [1] reported that 79% of global plastics are buried or lying on the landfill surface, contrary to the perception that the ocean and sea are major depots of MNPs. The major difference between MNPs in the aquatic and terrestrial environments is the ease of dispersal of MNPs in the marine environment due to their buoyant nature in water [19].

MPs in the soil and agroecosystem emanate from two major ways, resulting in varying sizes of plastic: the primary and secondary sources [20]. Primary sources of MPs are instantly propagated into the environment in micro, and nano-sized forms [21], and they constitute plastic pellets, micro-beads in cosmetic formulation, artificial grass, sewage sludge, paint, and vehicle tyre wear [20]. They can also be generated by the abrasion of plastic items during the manufacture, usage, or maintenance process. This could include the eroding of tyres during driving or the attrition of synthetic materials while washing [22]. Meanwhile, secondary sources of MPs originate from the breakdown of bigger plastics into smaller fragments. These large plastics could be bottles, plastic bags, fishing

Table 1
Occurrence and distribution of MNPs in different agroecosystems.

Location	Country/ Continent	Abundance (items/kg unless otherwise statedPara Run-on–>	References
Saltwork East coast of China	China/Asia	734	[31]
coastline soil of Shandong Province	China/Asia	1.3–14,712.5	[32]
Farmlands of Harbin City, Heilongjiang Province	China/Asia	107	[33]
Agricultural soil, Xinjiang province	China/Asia	40.35 mg/kg	[34]
Shaanxi Province	China/Asia	1430–410	[35]
Loess Plateau	China/Asia	40–320	[36]
Tianjin City	China/Asia	95	[37]
Farmland in Tibetan Plateau	China/Asia	20 to 110	[38]
vegetable farmland in a suburb of Wuhan	China/Asia	320 to 12,560	[17]
Agricultural land of Nanjing and Wuxi	China/Asia	420–1290	[39]
farmland soils in suburbs of Shanghai	China/Asia	8.00 ± 12.91	[28]
rice-fish culture stations of Shanghai	China/Asia	10.3 ± 2.2	[40]
mulching vs. non-mulching soil cropped soils In Hangzhou Bay	China/Asia	571.2 vs 262.7	[41]
soils randomly collected from Yunnan province	China/Asia	9.8×10^3	[42]
cropped areas at Dian Lake ranges	China/Asia	18,760	[43]
Woodland vs vegetable land vs vacant land In Wuhan	China/Asia	4.1×10^5 vs 1.6×10^5 vs 1.2×10^5	[44]
Sewage sludge disposal soil	Chile	18–41	[45]
Cropland vs pastures Chile's Región Metropolitana	Chile	306 ± 360 vs 184 ± 266	[46]
Sydney Industrial area	Sydney	300–6900	[47]
freshwater wetland in Kenilworth Park and Aquatic Gardens in Washington	United State	1, 270 ± 150	[48]
Floodplain, Lahn River area	German	1.88 ± 1.49–8.59	[49]
Farmland of Franconia, Germany	Germany	0.34 ± 0.36	[50]
catchments and the textures of the floodplain soils	Switzerland	55.5 mg/kg	[51]
Home garden soil, Campeche, SE Mexico	Mexico	0.87	[29]

waste, and other huge plastic waste. Secondary MPs accumulate due to weathering of mismanaged material such as plastic bags, fishing nets, and other mismanaged waste [23]. The origin is difficult to trace because of their degradation, thereby making their conversion rate difficult to determine [22].

Conversely, the occurrence of plastic in soil and agroecosystems varies across different geographical locations and depends on population density and the nature of the activities the populace engages with. Hence it is interesting to review the occurrence and distribution of MNPs in agroecosystems around the globe to properly position strategies to combat their severe consequence on food security and human health [24]. Although there are no sufficient data to provide conclusive evidence on the occurrence and distribution of MNPs in the agroecosystem, Yang et al. [25] presented a schematic workflow to estimate the spatial distribution of MNPs in an environment. Nizzetto et al. [26,27] recently estimated that European farmlands are covered with about 63–430 thousand tons of MNPs while about 44–300 thousand tons in North America. In China's busiest city, Shanghai, it was estimated that 62.5 MNPs items per kilogram of deep soil and 78.0 items per kilogram of shallow soil [28]. From Mexico, another group of scholars estimated that 0.87 ± 1.9 particles per gram of soil around Campeche city, Mexico, South America [29]. Finally, it was reported that soil samples around industrial areas in Australia contained around 0.03–6.7% MNPs (Table 1). It is interesting to note that there are no reliable data available to understand the occurrence and distribution of MNPs in agroecosystems, despite the constant rise in plastic pollution and its improper disposal [24,30]. Therefore, there is a need for more studies to focus on the generation of data and estimate to measure the MNPs occurrence in geographical regions where such information is lacking. This information is necessary first to accurately make future projections and could serve as a clue to proffer a solution to the menace of plastic pollution (Alimi et al., 2021).

3. Fate and transport of micro-and nanoplastics in soil and agroecosystem

MNPs populated within the soil of a particular location have a high tendency to migrate to other locations or are distributed either by vertical and horizontal migration or transportation by biological and non-biological agents [25,52]. The majority of MNPs on the agroecosystem are deposited on the top surface of the soil and migrated vertically to other soil strata [52]. Moreover, surface MNPs are prone to be carried away by running water, wind and flood to other locations – hence, referred to horizontal transfer of MNPs. Similarly, human activities such as preparation and distribution of composting [53], sewage sludges [54,55] and irrigations [56,57] contribute to the horizontal transfer and distribution of MNPs [28] majorly as a result of agricultural activities.

Several other factors contribute to the downwards movement of MNPs; some of them are – the soil pore sizes which can be prone to leaching for larger pore sizes; bioturbation activities of the plants' roots caused by the root movement, root expansion, root water extraction; cracks in the soil structure as a result of dry climate and others [25,58]. The fate of MNPs transported downward through the soil could mainly join shallow groundwater, which further enhances their distribution [53,59]. Finally, it is important to note that soil fauna could contribute to MNPs' horizontal and vertical transportation [55]. It was recently reported that soil organisms such as

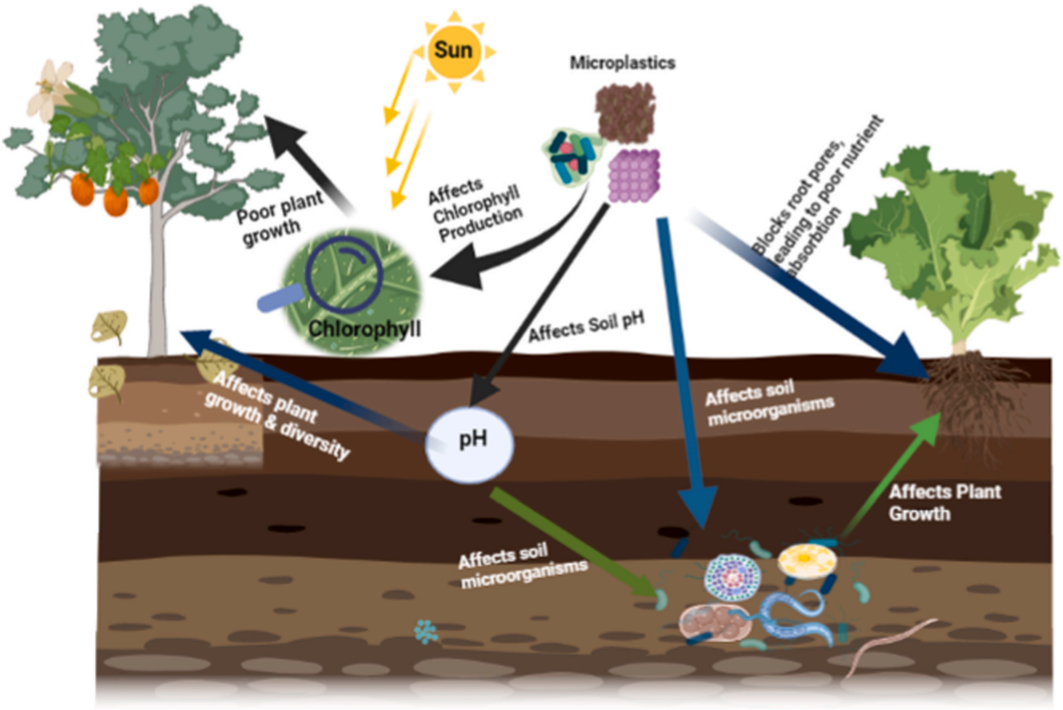

Fig. 2. Occurrence, transport, and the fate of MNPs in agroecosystems. MNPs are distributed in agroecosystems horizontally and vertically, affecting plant diversity, soil biota, and nutrient cycling. This results in severe ecological risks.

earthworms and collembola species promote the transfer of MNPs due to their surface adhesion properties and ingestion and excretion of MNPs at different soil locations [60,61]. Fig. 2 shows the occurrence, fate, and transport of MNPs in agroecosystems.

4. Impacts of micro-and nanoplastics on soil and agroecosystem

There have been increasing concerns on the extent of MNPs impact on soil organisms, microbial community shift, and ecosystem processes such as organic matter decomposition and nutrient cycling [62,63]. Growing evidence demonstrates the negative effects of MP residues on soil flora, soil quality, and crop production [64–66]. Gao et al. [67] found that exposure to polyethylene (PE) interfered with the antioxidant defense system in lettuce and significantly reduced its growth, photosynthetic ability, and chlorophyll content. Similarly, MPs has been reported to hinder shoot growth [62], inhibit water absorption by blocking seed pores, causing a delay in germination and growth of plant roots [68]. Polypropylene (PP), Polyamide (PA), and HDPE particles reportedly decreased the root and fruit biomass of *Allium fistulosum* (spring onions) [69], while biodegradable plastic and LDPE MPs were found to reduce growth patterns in plant height, number of tillers, and fruits of *Triticum aestivum* (wheat) [70]. A recent study conducted to determine the effect of MPs on tomato yield revealed that the presence of MPs enhanced the growth of tomato plants but delayed and reduced fruit production [71].

On the other hand, the presence of MNPs in the agroecosystem directly and indirectly affects the soil fauna, resulting in various toxicological effects [72,73]. Due to its relatively small size, soil organisms can ingest MPs, resulting in potential physical and chemical damages [1]. Also, MPs can remain in the intestines of soil fauna long after being excreted [74], even altering the intestinal microbiota, which is crucial for the utilization of organic matters and soil element cycling [75,76]. Recent studies revealed that different particle sizes of polystyrene induced gut microbiota dysbiosis, intestinal barrier dysfunction, and metabolic disorders in mice [77,78]. Furthermore, depending on the type and concentration, MPs can cause growth inhibitions and impairment of the immune system, as seen in studies on earthworms [79–81].

Alterations in soil properties resulting from MNPs have been suggested to be responsible for the changes in the activities, structure, and composition of soil microbial communities, even though no solid evidence or robust linkages have been verified [82]. The actual effects of MNPs on microbiota vary considerably between reported studies. Yi et al. [83] reported a significant change in the α diversity and the abundance of soil microbial communities induced by membranous PE and fibrous PP, in which the abundance of Acidobacteria and Bacteroidetes increased, while the abundance of *Deinococcus thermus* and Chloroflexi decreased simultaneously. Laboratory studies conducted on cellulose acetate, a MNPs contained in filters of cigarette butts, revealed a significant effect of the MPs on the β diversity of soil bacterial communities [84]. Different MP types can induce varying effects on soil microbiota (Fig. 3). De Souza MacHado et al. (2018) found that PA and PE caused a significant increase in microbial activity, whereas Polyester and Polymethyl methacrylate decreased microbial activity. More so, MPs can become shelters for microbes and promote their survival even under adverse conditions by forming layers of biofilms referred to as "plastisphere" [85,86]. However, this protective mechanism can become a habitat for the proliferation of pathogenic and potentially harmful microbes [87]. Conversely, several studies have found no significant effect of MPs on soil microbiota [88–90]. While others have highlighted the negative impact of MPs on microbial processes, such as its inhibitory effect on the dissipation of soil antibiotics and some antibiotic resistance genes [91], including its adverse effect on soil enzymes (urease, glucosidase, and phosphatase) [92].

Recent studies have found that the coupling between carbon and nutrient cycling can be altered by the presence of MPs in contaminated soils through significant increases in CO_2 fluxes and dissolved organic matter [93,94]. For instance, Gao et al. [54] found

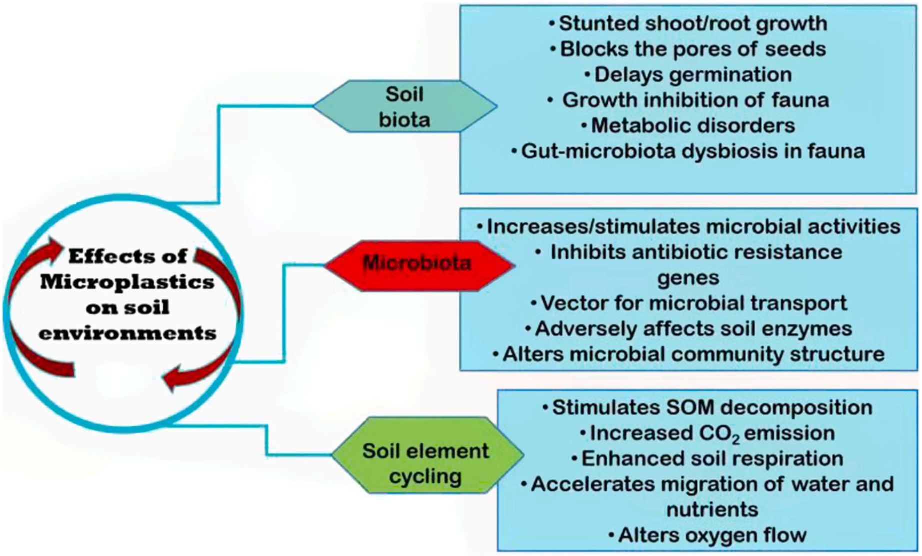

Fig. 3. MNPs impact on the soil ecosystem. MNPs affect the soil biota, microbiota, and soil element cycling.

that the presence of MPs caused an increase in NH_4^+ concentration, a decrease in the NO_3^- concentration, and increased soil CO_2 emission by 28.67% (at 18% concentration of MPs). Although the soil nutrient utilization efficiency diminished, the impact of MPs addition on global carbon and nitrogen cycles was highlighted [54]. Liu et al. [95] found that C, N, P nutrients in the dissolved organic matter (DOM) were greatly enhanced by high levels of PP (approximately 30% w/w) present in the soil, suggesting that the MPs promoted soil enzyme activity and the accumulation of soluble nutrients. In addition, PP enhanced soil respiration by 3-folds, increased fluorescein diacetate hydrolase activity, and stimulated SOM decomposition [95]. According to the organic-organic persistence hypothesis, MPs can induce a negative priming effect due to the dilution and adsorption of soil available C (i.e., DOC) to their plastic surfaces [96]. MP residues have been reported to promote soil porosity resulting in changes in its water cycling properties [97], even accelerating the migration of water and nitrate at high concentrations (360 kg/hm2) [98]. These changes further cause a shift in soil oxygen flux and influence the abundance of anaerobic or aerobic microorganisms in the soil [99]. Recently, the addition of different MPs (LDPE and biodegradable) reportedly decreased the soil conductivity and increased its pH and carbon-nitrogen ratio [100]. However, most studies on the role of MPs in soil biogeochemical cycles are based on laboratory simulation data. Therefore, field-scale experiments are necessary to establish these findings.

5. Uptake of soil micro and nanoplastics in plants

MNPs are thought to be unable to be absorbed by terrestrial plants because their big size and high molecular weight prohibit them from passing through the cellulose-rich cell walls [101]. Recent research has found evidence that when MP and NP particles are broken down into nanoparticles, they can cross cell membranes and enter plant cells [102]. A study demonstrated that BY-2 cells from tobacco could take up nano-polystyrene (0.02 and 0.04 μm) in cell culture by endocytosis [103]. Similarly, a study looked at the absorption and distribution of fluorescently tagged polystyrene (PS) microbeads of 0.2 and 1.0 μm in lettuce plants. Fluorescence was detected in the lettuce plants exposed to 0.2 μm PS beads, demonstrating that terrestrial plants can pick up MNPs from the soil and transport them from the roots to the shoots. Very little luminescence was observed in lettuce plants subjected to 1.0 μm [104]. Nanoparticle uptake by whole plants, such as rice, maize, and soybean, has also been reported in other researches [105,106]. Several parameters, including the MNPs size, shape, surface charge, and chemical makeup, influence MPs uptake and toxicity in plant species [102,107,108]. Transpiration is primarily responsible for the absorption and translocation of nanoplastics in terrestrial plants. As a result, factors that affect transpiration rate may have an impact on nonoplastic migration in terrestrial plants [109]. Nanoplastic accumulation in plants can have both direct and indirect ecological consequences, as well as a negative impact on agricultural sustainability and food safety. However, based on current data and evidence, most studies and researches on MNPs uptake by plants are conducted in the laboratory, which may not reflect real-world circumstances in terrestrial agroecosystems.

5.1. Mechanism of uptake of soil MNPs by plants

MNPs are frequently unable to enter plant tissues directly due to their huge size, which prevents them from penetrating plant cell walls [101]. However, a recent study has revealed that vascular plants may absorb and store larger quantities of MPs [110]. Depending on their size and kind, MNPs can permeate seeds, roots, stems, leaves, fruits, and plant cells. Bandmann et al. [103] demonstrated plant uptake of micro(nano)plastics when they saw fluorescent polystyrene (PS) nanoparticles being taken up by tobacco BY-2 cells via endocytosis. Recent research has revealed that many plant species can take up micro (nano) plastics of various sizes and polymer types. According to previous research, plants can translocate nanoplastics from the soil to the leaves via their roots, and this process involves plant vascular tissues [111]. PS nanobeads (50 nm) have been found to reach the cytoplasm and aggregate in peat moss hyalocysts [112]. The cytoplasm and vacuoles of Allium cepa can also accumulate 50 nm PS nanobeads [113]. The buildup of nanoplastics in vacuoles and cytoplasm of the root epidermis of Allium cepa was attributed to the small size of the nanoplastics, which allows them to pass through membranes [113].

Researchers have recently begun investigating the mechanisms of MNPs absorption and translocation in plants. Plants can absorb or adsorb MNPs, and transpiration pull plays a key role in plastic particle uptake and translocation [114]. *For example, T. aestivum and L. sativa* can internalize PS nanobeads [115]. According to the authors, these beads could penetrate the root stele and subsequently pass from root to shoot due to the transpirational pull. Plastic particles enter the epidermal tissue of wheat's roots, are stimulated through the pericycle, and transferred into the xylem from where they can migrate to the aerial section of the plant through the xylem inside the central cylinder according to a study by Li et al. [34]. Confocal pictures taken during the study indicated that plastic luminescence signals were found mostly in the stem's vascular system, implying that the water potential gradient caused by plant transpiration was the driving force for micro(nano)plastics to travel in plant vascular systems. PS nanospheres (100 nm) were found in the root and shoot xylems of wheat plants after 21 days of exposure in a hydroponic investigation, demonstrating the critical function of the vascular system in the upward transfer of micro(nano)plastics in terrestrial plants [111]. The symplast route allows very small plastic particles to enter root cells and go to the root xylem. The apoplastic channel could be the main transport route in plant roots for particles with comparatively greater diameters [116].

Another avenue for plastic penetration into plants and uptake of MNPs by plants is through the stomata. A recent study by Sun et al. [102] reported that stomatal uptake is one probable avenue for NPs to enter the leaves and proceed to the vasculature. The authors demonstrated the migration of NPs from the leaves to the stems and then from the stems to the roots through the vascular bundle using fluorescence microscope imaging analysis. Similarly, another research showed that PS NPs connect to the stomata, enter via the phloem, and reach the lettuce plant's roots [117]. The understanding of MNPs absorption and accumulation in plants is currently relatively poor. In-depth research into the mechanisms of MP and NP absorption and transportation in plants is necessary.

5.2. Effects of soil MNPs on plant growth and development

Plants are a foundational living component of terrestrial agroecosystems. The prevalence of various types of MNPs in soils leads to their interaction with terrestrial plants. The possible impacts of MNPs on terrestrial plants are creating increasing concern due to the critical role of plants in terrestrial ecosystems and the continuous emission of MNPs. The permanence, variety, and abundance of MNPs in terrestrial habitats and agroecosystems have been shown to affect plant growth and development in a variety of ways, but the specific effects vary significantly depending on plant species and MNPs properties [118,119]. MPs can have an indirect effect on plants in an agroecosystem by influencing soil texture, physiochemical characteristics, soil microbial community, and root symbionts in the rhizosphere, or a direct effect by blocking the seed pore, immobilizing nutrients in the soil, and limiting nutrient uptake through roots (Fig. 4). The majority of studies on the impact of MNPs on terrestrial plants are conducted in the lab with known concentrations of specific MNPs, which may not be representative of conditions in terrestrial agroecosystems where there is a mixture of MNPs as well as other pollutants. To fully comprehend the crucial interaction between MPs and terrestrial plants, more research using a mixture of MPs and other micropollutants in actual environmental settings is required.

5.2.1. Direct effect on plants

MNPs can be phytotoxic and directly inhibit plant growth. The toxic effects of MPs on plants are influenced by size. The smaller the size of the MPs, the greater the toxicity to plants [104]. For example, MNPs can be degraded or broken down in nanoplastics which are so small that they can cling to the root surface or accumulate in the root vascular system thereby limiting water and nutrient uptake by afflicted plants [102,120]. Seed germination can also be hampered by MPs attaching to the surface of seeds and physically obstructing pores, causing delay in germination [68]. In a recent study, it was observed that after 8 h of exposure to NPs particles, seed germination was drastically decreased when compared to a control group [68]. The low spouting rate of seeds was attributed to physical obstruction of the seed pores and root hairs by nanoplastics.

The effect of different types of MPs particles (low-density polyethylene (LDPE) and (starch-based biodegradable plastic) of sizes (1 mm, 500 μm, 250 μm, and 50 μm) present in sandy soil on wheat plants was investigated utilizing an environmental chamber. The result revealed varied effects of MPs on wheat plant growth during both the vegetative and reproductive phases [121]. Similarly, a recent study investigated the effect of six different MPs on the growth performance of spring onion was investigated and significant changes in plant biomass, root traits and tissue composition were observed. In another experiment using maize plant, it was observed that when compared to control plants, MPs bioaccumulation in the rhizosphere resulted in a 50% drop in biomass and plant height, as

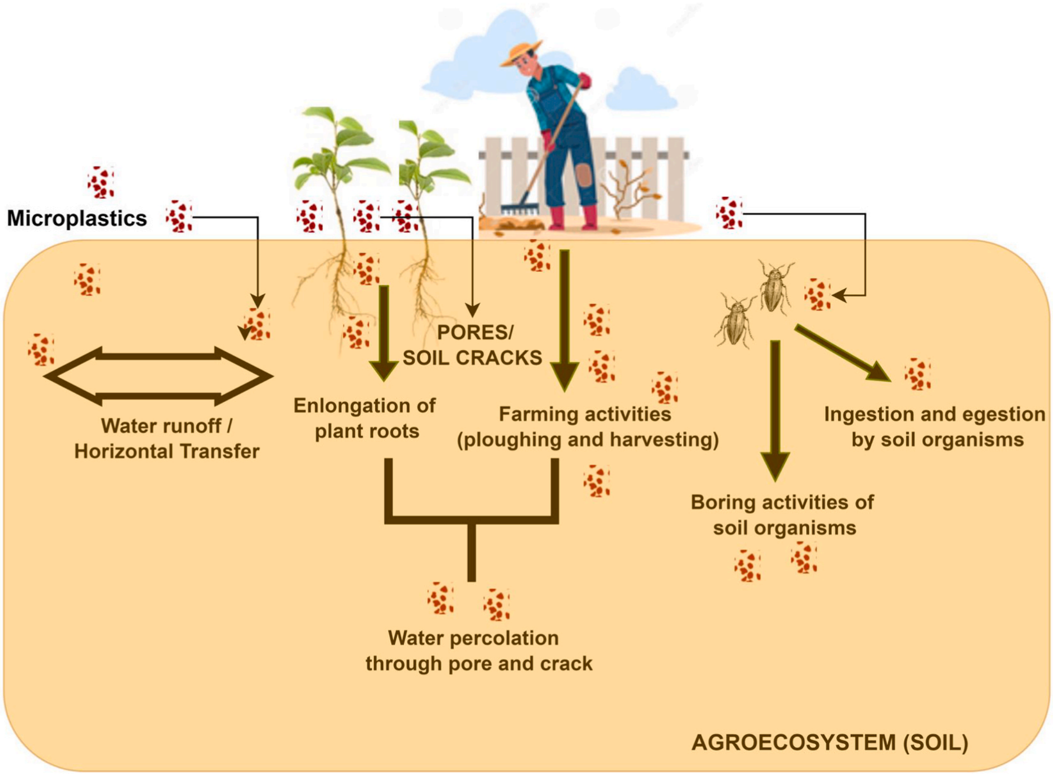

Fig. 4. MNPs impact on plants. MNPs attach to plant roots hairs and limit the uptake of nutrients. They can also be absorbed directly by plants and taken up to the leaves, where they affect chlorophyll production, leading to limited photosynthesis and poor growth. MNPs can also alter the pH of the soil, which affects soil microbes and invariably plant growth and performance.

well as a dramatic decline in transpiration rates and nitrogen content [120]. MPs have been shown to limit plant growth and development in a variety of other plant species, including rice, maize, carrot, and onion [113,122–124]. Nanoplastic exposure to terrestrial plants has also been shown to have a negative impact on the development of chlorophyll in plant shoots or leaves, showing that nanoplastics may impede the process of photosynthesis [122,125]. Excessive accumulation of reactive oxygen species (ROS) in chloroplasts occurs when plants are exposed to nanoplastics, which may be responsible for the observed decreased chlorophyll production. Nanoplastics cause oxidative stress in terrestrial plants, as indicated by increased generation of reactive oxygen species (ROS) and enhanced antioxidant enzyme activity which suggests that nanoplastic particles can cause oxidative damage to terrestrial plants [124]. However, it's important to note that the specific effects of nanoplastics on terrestrial plants varies with plant species and the type of nanoplastic. For example, it was observed that the photosynthetic rate of wheat was enhanced when exposed to a low dose ($\leq$0.1 mg/L) of PS particles but was inhibited when the exposure dose was increased ($\geq$1.0 mg/L) [111]. The authors attributed this phenomenon to dose-dependent hormesis. Nanoplastics can also affect the metabolic pathways in terrestrial plants. The majority of primary and secondary metabolites were altered in hydroponically grown rice leaves exposed to PS nanoplastics, and the concentration of these metabolites decreased as the exposure dose increased [124]. Plant intake of nutrients, energy production, and biosynthesis can all be hampered by changes in metabolic pathways, resulting in stunted plant growth and development [124,119].

5.2.2. *Indirect effects on plants*

Contamination of soils by MNPs can result in changes in soil structure as well as biophysical and geochemical structural aspects (Rillig and Lehmann, 2019). The functional variety of the soil microbiota, as well as the growth of nitrogen-fixing bacteria and mycorrhizal fungal communities in the rhizosphere, may be reduced as a result of this shift in soil structure and composition. Because nitrogen-fixing bacteria and mycorrhizal fungi are so important to soil fertility, plant development, and performance, reduced microbial activity by MPs could have a direct influence on plant growth and performance [121,126,127]. Plant variety and community composition may be influenced by MNPs. Soil structure influences plant diversity and community [128]. As a result, the considerable effects of diverse MPs types on soil structure can have an impact on the composition, diversity, and productivity of plant communities. Contamination of terrestrial agroecosystems with MPs, for example, could reduce plant diversity due to the typically favorable effect of soil microbial diversity and rhizosphere microbes on plant diversity [129] However, in terrestrial ecosystems with high MPs contamination, such effects on plant populations and variety are more likely to occur. Some MPs can lower soil pH, which can affect microbial growth (Boots et al., 2019). Changes in the pH of the soil are can potentially cause alterations in the general microbial communities of the soil and rhizosphere [130]. However, the mechanism by which MPs alter the pH of the soil is not understood. Further research to unravel the mechanism behind this change in soil pH as a result of MPs contamination is highly recommended.

5.3. *Effects of soil MNPs on food chain*

Just as several studies on microplastic of aquatic/marine ecosystems have proven to be a nuisance causing several adverse effects on living organisms and the environment, microplastic in the soil and agroecosystem have similar impacts [59]. More so, microplastic in the agroecosystem could have serious effects on human health as a result of trophic transfer from food chain [12]. MNPs from the agroecosystem poses significant health problems that have become an emerging concern [131]. The possibility of MNPs bio-accumulating in the body through several means of exposure ranging from drinking MNPs contaminated water to consuming MNPs contaminated agro-produce depict the high risk of MNPs on human health [132–135]. It was reported that an average adults and children intake of MPs per year is 1063 particles and 3223 particles, respectively [136]. The ingested and bioaccumulated microplastic MNPs in humans raises serious health problems highlighted in this section.

The trophic transfer is one major process MNPs migrate from lower organisms to higher mammals [137]. Evidence from past studies has shown remains of plastics from lower species such as otoliths of lantern fish (*Electrona subaspera*), the faeces of Hooker's sea lions (*Phocartos hookeri*) and fur seals (*Arctocephalus* sp.) [59]. Moreover, the hypothesis of food chain/webs state that MNPs can be transferred from the organism in the lower trophic level, which are usually prey to organisms in higher trophic levels (where higher mammals and human belongs), Hence across the trophic levels, MNPs tends to bioaccumulate or biomagnifies both in the higher organism for marine and agroecosystem [7,25,29,138].

Studies specific on trophic transfer of MNPs in the agroecosystem are sparsely available. Recently, Huerta Lwanga et al. (2017) discovered a reasonable amount of MNPs in the faeces and gizzards of chickens' feds with MNPs-free crops. It was predicted that the MNPs in the gizzards and digestive tract of chicken might be due to the conversion of macroplastics to MNPs. Or the consumption of lower invertebrates such as earthworms possibly accumulates the MNPs from the soils (agroecosystem) [29]. Moreover, they reported that the abundance of MNPs consistently increased from soil (0.87 ± 1.9 items/g) to earthworm casts (14.8 ± 28.8 items/g) to chicken faeces (129.8 ± 82.3 items/g) [29]. Other reports have shown MNPs present in other lower invertebrates, mainly the food chain's primary consumers. Some other organisms are springtails [139], nematodes [140], and snails [141]. Another study recently discovered MNPs invaluable organs of mice such as the liver, kidney and gut. This finding suggests that higher organisms bioaccumulate MNPs in their vital organs, increasing the risk of organ failures and other debilitating conditions [142]. In the same vein, a more recent study detected the presence of MNPs traces in human stool and colectomy and suggested that MNPs are readily bioavailable in humans and cannot be degraded as they migrate through the digestive tract [143,144].

Apart from the well-known trophic transfer/food chain pathway for MNPs transfer to get to a human, studies have reported alternative routes such as inhalation of fine particulate matter; ingestion of salts, drinking of water, tea from tea bags and other MNPs contaminated foods [145,146]. There are very limited data to understand the associative health risk of MNPs on humans comprehensively. Deduction for other studies has shown the adverse impacts on the intestines on marine organisms [147,148]. At the same time, studies on poultry birds have shown MNPs to cause oxidative stress, inflammation, and other forms of particulate toxicity that could eventually progress to tumorigenesis [29]. Therefore, there is a need for more studies to specifically identify the health impact of MNPs on humans [149].

5.4. Effects of soil MNPs on nutrient cycling

Much attention has not been paid to how MNPs influence the terrestrial agricultural ecosystems. The presence of microplastics has the potential to alter not only the functional diversity, microbial biomass, and microbial activity of the soil but also the dynamics and cycling of nutrients in the soil [150–154]. The presence of polyethylene and polystyrene in the soil has been associated with a reduction in the activity of two key enzymes involved in nitrogen cycling: leucine aminopeptidase and N-acetyl-glucosaminidase. This suggests that there may be implications for the availability of nitrogen in the soil due to the incorporation of these materials [155]. In the past, microplastics like polypropylene tended to amass larger quantities of dissolved carbon, nitrogen, and phosphorus in soil solution. This was mainly driven by the enhanced activity of extracellular enzymes [95].

According to Huang et al. [88], microplastics such as polyethylene can influence the hydrolysis of nitrogen, as evidenced by the observed greater level of urease activity in polyethylene. Nitrification is a crucial part of the nitrogen cycle; because of the major consequences for both the health of the soil and the stability of the ecosystem, it frequently calls for stringent monitoring. It plays an important role in the ammonification process, often where the N mineralization process ends. Recently, biodegradable plastic made from polylactic acid has been shown to have major adverse effects on the environment. These effects may be seen in the decreased concentration of NH_4 in the soil and the increasing concentrations of NO_3 and NO_2 [17]. Therefore, it is abundantly obvious that the impacts of microplastics on the cycling of nitrogen are possible, which also calls for more study that confirms the findings by utilizing a wide variety of microplastic materials. Certain microplastics, such as polyaramide, polyacrylonitrile, and polyamide, enhance the availability of biogeochemically active nitrogen. However, sometimes their derivatives, such as phthalate esters, may contaminate soil, disrupting nutrient cycling by limiting the activity of key soil enzymes [156]. In addition, these compounds have the potential to form complexes with chemicals that are liberated during the breakdown of organic material and the degradation of plastic, which may eventually affect the processes of decomposition and ammonification.

As MNPs component make up contains a lot of carbon, often about 80% [157], which sets them apart from other components that contribute to global warming. One possible exception is pyrogenic carbon, which also contains a high percentage of carbon. MP carbon is therefore already present in the soils, although it likely still makes up only a small portion of total soil organic matter. However, this might change in time, because MP does seem to be resistant to microbial decay compared to plant residues [157]. It is possible for a relatively low yearly intake to transfer into a quantitatively important accumulation over extended periods, as was found with pyrogenic carbon [158]. Microplastic-carbon's (MP-C) origin and functionality is different from the rest of the soil organic carbon. The current technique for quantifying soil C has not distinguished the MP-C from the soil organic matter carbon. This is concerning because the storage of soil organic C is an ecosystem contribution. The separation of these two organic carbon sources is necessary. Still, the means to do so on a routine basis are not now accessible since the procedures for MP measurement are still being developed and perfected. Once they have reached the soil's surface, MP particles have the potential to rapidly get absorbed into the soil matrix.

5.5. Effects of soil MNPs on global warming

Several studies have shown that MNPs influence greenhouse gas emissions [94,159,160]. There is a need to properly understand the processes responsible for this phenomenon. Although it has been observed that MNPs are prevalent in the marine environment; comparatively little study has been carried out on the terrestrial system. In the study by Ref. [94]; they reported the effect MNPs have on the fluxes of greenhouse gases. According to their findings, the presence of MNPs in fertilized soil at a concentration of 5% (w/w) did not significantly influence the content of dissolved organic carbon over a short period.

On the other hand, the composition of dissolved organic carbon was connected to the particle size of MPs. During the first stage of the experiment, which lasted 30 days and took place in fertilized soil, the presence of MPs resulted in a lower Global warming potential. This was because MPs had a diminishing effect on the emission of N_2O, which altered the abundance of microbes responsible for the uptake of CH_4 and the emission of N_2O.

Rillig et al. (2021) showed indisputable evidence that microplastic fibers affect the dynamics and strength of greenhouse gas fluxes, such as CO_2 and N_2O. Their studies reveal that microplastics might reduce the enhancement of N_2O emission caused by extensive N fertilization. The evidence suggests that the introduction of microplastics has had a significant impact on the emissions of CO_2 and N_2O, mostly through modifications to the soil structure. There was observed concurrent change in the fraction of water-soluble aggregates and the gas fluxes in the different variations that contained microplastics. Their findings do not, however, give any information on the precise soil structure factors that were responsible for the altered CO_2 and N_2O fluxes. This calls for more research to be conducted on the precise measurement of the gas movement in the soil and how it will affect global warming and climate change.

5.6. Importance of nanoparticles and micro-particles in agroecosystems

Nanoparticles and micro-particles play a significant role in the agroecosystem due to their unique physical and chemical properties. These particles have the ability to enhance the efficiency of fertilizers, pesticides, and other agrochemical inputs, leading to increased crop yields and improved soil health (S. S [161–163].

Some of the key benefits of nanoparticles and micro-particles in agroecosystems include:

a. Increased nutrient uptake: Nanoparticles and micro-particles can be used to encapsulate nutrients, such as nitrogen and phosphorus, making them more readily available to plants. This leads to improved nutrient uptake and increased crop yields [164].
b. Improved pest control: Nanoparticles and micro-particles can be used to deliver pesticides in a targeted manner, reducing the overall amount of pesticide needed and minimizing potential negative impacts on the environment [165].
c. Enhanced soil health: Nanoparticles and micro-particles can be used to improve soil structure and water retention, leading to healthier plants and increased crop yields [163].
d. Increased crop yields: The use of nanoparticles and micro-particles can lead to increased crop yields due to the improved efficiency of fertilizers and pesticides, as well as improved soil health [166].

6. Analytical methods for the measurement and detection of micro-and nanoplastics in agroecosystem

In recent years, not many topics have received more attention than those concerning MNPs and their emerging environmental impacts. Though studies on the identification of MNPs and their effects on the marine ecosystem have been widely carried out [167], their impacts on the soil ecosystems have not been explored, as much was not known about their emerging impacts on the terrestrial environment until recently in 2018 [50]. Considering the potential effect of MNPs on soil biodiversity and function, this section aims to review the analytical methods used in detecting/identifying, and measuring MPs in agroecosystems.

Microplastics are emerging particulate anthropogenic environmental pollutants and have recently become a research area with growing interest from scientists and the general public. These tiny particles are extremely complex and diverse in size, shape, density, polymer type, surface properties, etc. Detection and measurement of these complex and widely varied MNPs samples may not be possible unless appropriate analytical methods are applied [168]. The researcher, therefore, requires adequate information about the diversity and broad ambient concentration range of MNPs in the samples (being analyzed). This is usually required and expressed in terms of MNPs mass and the number of particles in real samples (variation is up to 10 orders of magnitude, depending on the sample).

Apart from detection methods, the sampling and processing/preparation methods are also associated with MPs assessment. These methods are interdependent and are represented in Fig. 5. The selection of suitable detection methods depends largely on a safe and comprehensive investigation of the environmental media entry paths such as water, soil, compost, and sewage sludge. Preparation of the selected sample (for analysis) largely depends on three major factors: the environmental matrix to be examined, the sample quantity, and the detection method chosen.

According to Braun et al. [169], it is essential to specify the objectives and tasks of the project/existing requirements to effectively detect MNPs. This could involve determining the total content of the different plastics and analyses particle numbers and sizes for specific plastics. Even though a wide range of sampling techniques have been applied for monitoring MNPs in marine environments [170–173], MNPs still poses a significant challenge to scientists [168]. Watteau et al. [174] investigated the presence of plastics within compost and soil fractions using morphological and analytical characterization by transmission electronic microscopy (TEM-EDX) and pyrolysis coupled to gas chromatography and mass spectrometry (Py/GC/MS).

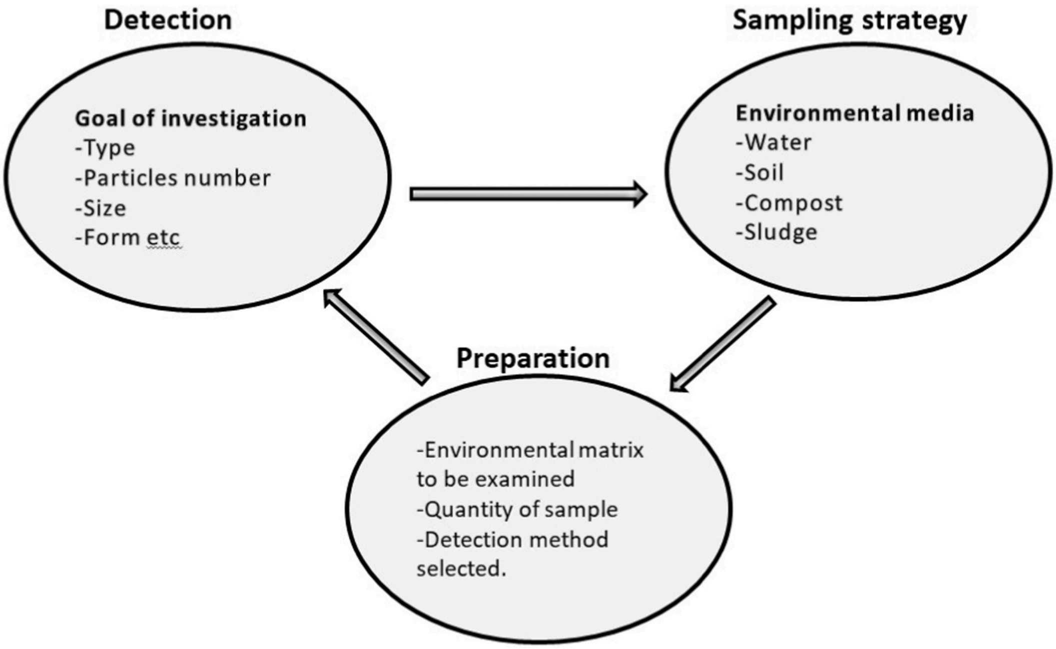

Fig. 5. Schematic representation of interdependencies during MNPs detection.

6.1. *Techniques for quantification and characterization of micro-and nanoplastics in soils*

The quantification of MNPs presence in a soil sample is vital not only for understanding their impacts and mapping their distribution but also for developing appropriate remediation plans. Precisely, there exist no bespoken widely acceptable techniques for the detection and measurement of MNPs in the soil. Detection of MNPs from soil samples typically require several processing of extraction and processing of the sample for to enable/ensure easy/efficiency of the method adopted. Typically, the most common and widely reported MNPs found in soil samples include PE, PP, PVC and PET. However, PE and PP are the most commonly found MNPs in a typical soil sample. The process of MNPs extraction from a soil sample requires that the target MNPs should be identified. Identification of the type, size and shape of the MNPs is a crucial first step to choosing a suitable detection method [175]. After the target soil sample has been identified, the next step is preparation of the soil sample. Preparation of collected soil sample involves drying, disaggregation, sieving, floating, filtering, or by using NaCl density-floatation separation method, depending on the nature of the soil organic matter.

Besides filter requirements, it is also necessary to ensure that samples are well mixed to avoid potential floating or sedimentation of MNPs. When high quantities of MNPs are present in the sample, care must be taken to avoid aggregation or overlapping particles in the filtering process. It is necessary to ensure that the sample is well mixed in order to avoid potential floating or sedimentation of the MNPs. Research has shown that no single method is adequate to effectively detect MNPs from complex samples [30]. Therefore, there is a need for a combination of reliable analytical methods. The basic techniques for MPs identification and quantification in soil samples include visual inspection (for large MPs samples between 1 and 5 mm), air-drying, density separation (using high density solutions such as NaCl, $ZnCl_2$, NaI), sieving, filtration (Fig. 6). Afterward, the samples are further identified by using the microscopic or spectroscopic techniques (non-destructive (FTIR or Raman spectroscopy)) and/or chemical identification analyses such and destructive (gas chromatography–mass spectrometry (GC-MS)). Table 2 shows the frequently used techniques for the detection and quantification of MNPs [169].

6.1.1. *Visual Microscopy (VM)*

This method involves the visual identification of MPs size, shape, texture and color using an electron microscope. It is a relatively fast method and suitable for the detection of large size particles (0.5–5 mm) [176]. It is possible to detect the size smaller MNPs when combined with high-resolution camera. Quality of the image and more details about the surface morphology can be improved using

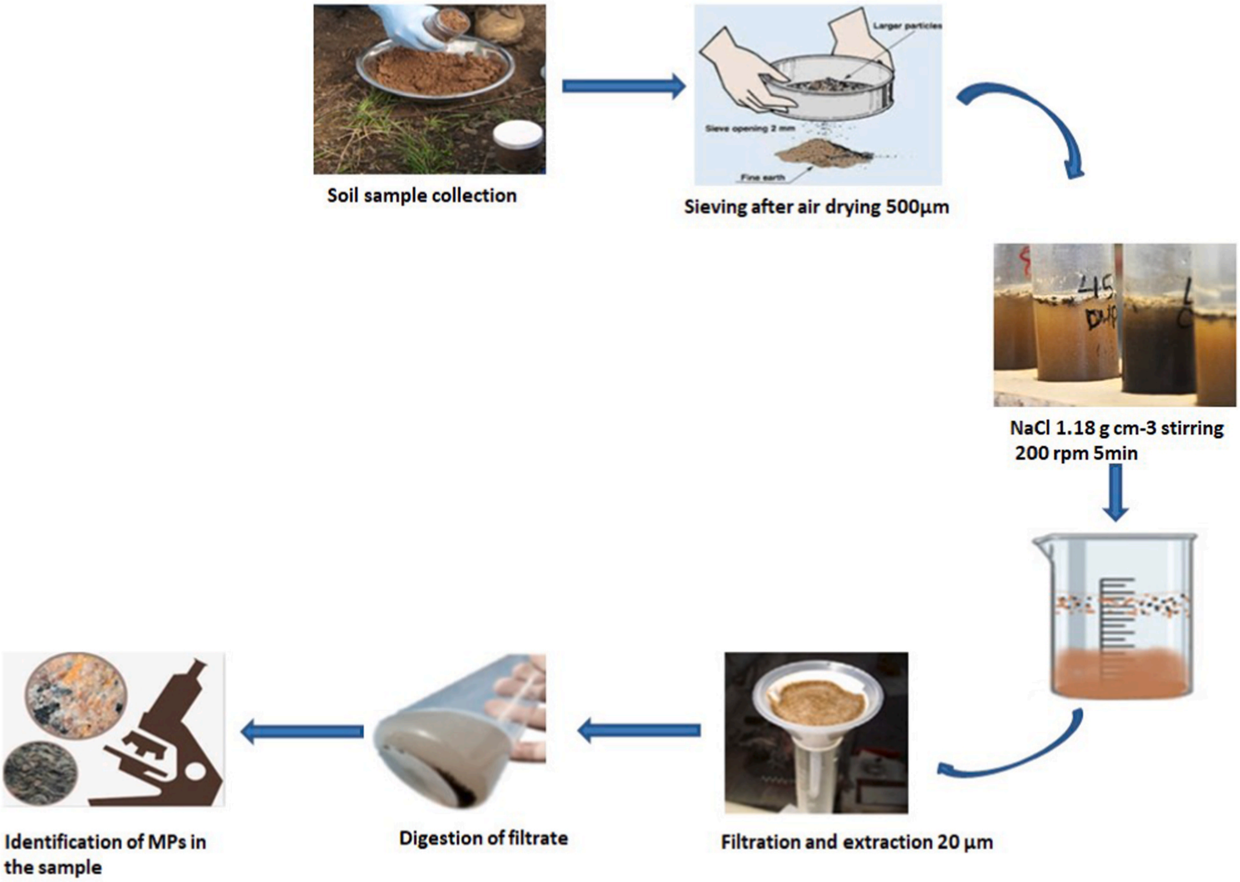

Fig. 6. Schematic representation of the MNPs extraction procedure using the NaCl floatation method.

Table 2
Frequently used techniques for the detection and quantification of MNPs (Modified from Braun et al. [169].

S/N		Cost	Technical requirement	Duration of test	No of particles	MP size range	Chemical identification	Accuracy
Common methods								
1	Visual/ microscopy	Cost effective	Requirements for professional training is low	Requires short time of testing	Countable	Suitable for large MPs (0.5–5 mm) but not suitable for medium (20–50 μm) and small (1–20 μm) MPs.	Not suitable for chemical identification	Low
2	FTIR	Expensive	High requirements for professional training	Requires short time of testing	Countable	Suitable for large (0.5–5 mm) and medium (20–50 μm) MPs but not suitable for small MPs (1–20 μm).	Suitable for chemical identification	Moderate
3	Raman	Expensive	High requirements for professional training	Requires short time of testing	Countable	Suitable for large (0.5–5 mm), medium (20–50 μm) and small (1–20 μm) MPs.	Suitable for chemical identification	High
4	GC-MS	Expensive	High requirements for professional training	Requires long time of testing	Numerous	Potential advantage to detect for large (0.5–5 mm), medium (20–50 μm) and small (1–20 μm) MPs.	Suitable for chemical identification	High
Extraction-free methods								
5	SEM/SEM-EDX	Very expensive	High requirements for professional training	Requires long time of testing	Numerous	Suitable for large (0.5–5 mm), medium (20–50 μm) and small (1–20 μm) MPs.	Potential advantage for chemical identification	High
6	Vis-NIR/HT-NIR	Very expensive	Requirements for professional training is moderate	Requires short time of testing	Moderate	Not conferred with the advantage of MPs size detection.	Suitable for chemical identification	Low

Scanning Electron Method (SEM) technique. However, the major shortcoming of this method is that it potentially has a low accuracy, which could be due to the influence of the operators' experience/judgment, eyesight, type of sample, location point of observation and the quality of the microscope. Another gas disadvantage is that it may not avail the inspector the ability to distinguish the types of plastics.

6.1.2. *Fourier Transform infrared (FTIR)*

The FTIR was introduced to overcome the limitations of Visual Microscopy. It is usually coupled with a microscope (micro-FTIR) and can screen MPs of medium size between 20 and 50 μm [34,177–179]. FTIR spectroscopy has been proven to be accurate and reliable in determining chemical identity and size of MPs. However, this method sometimes may not afford significant result due to 'refractive error which occurs as a result of the superposition of direct and indirect signal of the IR radiation by the asymmetrical shaped particle surfaces' [180,181].

6.1.3. *Raman Spectroscopy (RS)*

Raman Spectroscopy has similar features as the FTIR method in their detection accuracy of MPs and both follow non-destructive process. It has a high numerical-aperture objective and a short excitation wavelength, and unlike FTIR, Raman Spectroscopy can detect small size MPs of 1–20 μm [177–179,182]. The major setback of this method include long measurement time, expensive, signal to noise ratio is low, produces a lot of heat which could result to degradation of polymer interface due to pollutants [183].

6.1.4. *Gas chromatography-mass spectrometry (GC-MS)*

This is a destructive chemical detection analytical method of MPs with rapid and accurate ability to quantify the various MPs types (PE, PP, PS, PET) [184]. GC-MS method is not recommended where information about MPs size and number are requires. This is because the process of detection may lead to melting of polymeric particles in the sample.

6.1.5. *Near infrared (NIR)*

This is a direct method of MPs detection and does not involve/require going through the various processes of extraction. Ng et al. [185] noted that, with the aid of portable spectroradiometer with range between 350 and 2500 nm, it can successfully determine the concentrations of spiked MPs such as polyethylene terephthalate (PET) and low-density polyethylene (LDPE). The advantages of this technique over other of MPs detection techniques include their considerable economic and faster analysis [186,187].

7. Conclusion and future prospects

MNPs impact on the environment has been chiefly portrayed negatively in several studies, and agroecosystems are not excluded. MNPs in agroecosystems are linked to increased anthropogenic activity, with implications for food supply, nutrient cycling, and safety. However, appropriately implementation of the use of bio-based plastics, appropriate microbial remedial methods, regenerative agriculture, non-single-use synthetic plastic legislation, and increased plastic waste disposal awareness programs, among others, would go a long way toward reducing the volume and impact of plastic wastes.

Furthermore, there are glaring information gaps that will necessitate more coordinated efforts in future study, and the following concerns are of key significance:

- There is no standard procedure for isolating, quantifying, and characterizing MNPs in the soil. The development of a reliable, practical, and efficient assay for the detection and characterization of numerous MNPs is critical. Future study should focus on developing a testing methodology that accounts for the diverse ambient soil conditions as well as the variability of MNPs. It is important to standardize specific methods for collecting, isolating, identification and analysis of MNP samples agricultural soils rich in organic matter, according on their shape, origin, composition and size.
- MNPs may assist or impede the mobility and bioavailability of environmentally persistent and potential harmful contaminants in agricultural soils as vectors of a wide spectrum of pollutants. Although this field has received a lot of attention in aquatic ecosystems, there is still a lot of work to be done in terrestrial ecosystems, and future research will need to tackle this issue appropriately. MNPs are emerging persistent pollutants that have the ability to transfer across trophic levels in a food web. It's critical to figure out whether it has any cytotoxic effects on soil flora, animals, or humans, as well as assess any apparent transgenerational impacts. Animals, microbial communities must be studied in both natural and manmade ecosystems to understand their behavioral reactions to pervasive MNPs contamination in agricultural soils. As the dangers of MNPs have become more widely recognized, behavioral changes of plastic manufacturers and consumers would be required to achieve long-term plastic waste management.
- The worldwide and regional data inventory (concentration, types, compositions of MNPs) for the pollution status of MNPs in agricultural systems and soil ecosystems is currently quite inadequate and has to be significantly expanded. Future study should focus on the qualitative characterization and quantitative assessment of MNPs in various types of agricultural soils with various cropping systems, and their transformations and interactions in the rhizosphere, under varying climates.
- The amount of the database on the fate and sources of MNPs in the soil environment, as well as their interactions with microorganisms, soil animals and food crops are limited. To fully understand MNPs' environmental effects and consequences in the agricultural field, we must assess their transport, distribution and breakdown. MNPs are destroyed in part over time due to a variety of physicochemical and microbial factors. To understand the long-term fates of MNPs in the soil environment, it is critical to define the specific contributions of key anthropogenic and natural activities.

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