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Microplastics in agriculture: Hidden soil contaminants, sustainability risks and policy pathways

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ABSTRACT

Microplastics (MPs) are increasingly identified as a ‘hidden’ pollutant in agricultural soils, impacting sustainability and environmental resilience. Mulch films, irrigation systems and polymer-coated fertilizers have significantly improved agricultural systems, but because they are designed to persist longer, they pose ecological hazards and gradually break down into microplastics (<5 mm) and nano-plastics (<1 μm). MPs have therefore, been detected as notable vectors for heavy metals, persistent organic pollutants (POPs) and antibiotic-resistant genes through pathways such as agricultural materials, sewage sludge, and wastewater irrigation. Elevated MP levels affect the physico-chemical and biological properties of soil. These overlooked yet substantial changes may have an imperative consequence for groundwater and the overall food chain, ultimately jeopardizing long-term agricultural productivity and environmental sustainability. Regulatory frameworks around the world remain poorly integrated. The *EU Circular Economy Strategy*, *U.S. state-level monitoring*, *New Zealand stewardship schemes*, India “*the Plastic Waste Management (Amendment) Rules, 2024*” and “*China's Agricultural Film Recycling Action Plan*” are important steps in the right direction; however, regulation of agricultural sources remains insufficient. Mitigation strategies include the porous surfaces of biochar for MP entrapment, GAC filtration, enhanced pre-ozonation techniques, as well as innovative nanotechnology-based composites, phytoremediation, and microbe- and enzyme-based remediation. Notwithstanding, these strategies demonstrate potential efficiencies; however, operational barriers at a large-scale and integration with sustainable soil management practices still persist. Without effective mitigation and regulatory frameworks, progressive build-up of MPs in agroecosystems may have ecotoxicological risk for soil ecosystem functioning and sustainable food and agricultural systems.

1. Introduction

Plastic pollution has emerged as a significant global environmental issue owing to the widespread production, persistence, and accumulation of plastic materials across terrestrial and aquatic ecosystems. In the agricultural sector, plastic-based materials have played a crucial role in enhancing intensive and technology-driven farming systems by improving moisture conservation, pest control, nutrient management, and crop productivity [1,2]. Plastics are widely used as mulch films, greenhouse covers, drip irrigation systems, shade nets, controlled-release fertilizer coatings, and packaging materials, with plastic mulch films being extensively adopted in agriculture for regulating soil temperature, weed suppressions, and moisture conservations [3]. The large-scale utilization of agricultural plastics has been identified as creating severe implications for their environmental persistence and impact on soil ecosystems. Agricultural plastics are made up of long-lasting polymer materials such as low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) that break down by

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chemical, thermal, and physical processes to produce MPs (<5 mm) and ultimately NPs (<1 μm), where one MP can produce up to 10^{14} NPs during weathering [4,5].

Unlike aquatic ecosystems, where plastic pollution is markedly associated with industrial effluents and municipal solid waste, agroecosystems receive persistent plastic inputs primarily through agricultural intensification and diffuse non-point source pathways. Plastic mulch films, polymer-coated fertilizers, drip irrigation systems, greenhouse coverings, and shade nets are direct sources of MPs in soils as they are purposely introduced into agricultural fields for crop production and resource management. Following environmental exposure, these macroplastics undergo continuous mechanical breakdown and photooxidation in soils, ultimately generating secondary microplastics. In addition to direct agricultural plastics, agroecosystems are also indirectly contaminated through inputs such as compost, sewage sludge, wastewater irrigation, atmospheric deposition, and littering, which often act as imperceptible vectors for microplastics. Consequently, MPs persist and translocate via interactions with soil matrices, humic substances and biogeochemical components, ultimately entering crops, livestock, groundwater and broader trophic networks.

Agricultural soils require rigorous investigation as they serve as persistent sinks for MPs, where these polymers notably alter pedological, microbiological, and ecological dynamics. MPs modify bulk density, porosity, aggregation, aeration, and water-holding capacity, thereby altering nutrient cycling, hydraulic conductivity, and soil loss dynamics. A meta-analysis reported substantial MP accumulation in topsoil, averaging roughly 500 mg/kg within the 0-5 cm soil layer, equivalent to approximately 4.4×10^{11} particles/km^2 [6]. Furthermore, additives like UV stabilizers, antioxidants, pigments, and plasticizers are utilized to improve the mechanical and optical properties of agricultural plastics, thereby extending their environmental persistence [7]. MPs and NPs rapidly sequester a broad range of hydrophobic organic compounds (HOCs) including polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), pesticides, pharmaceutical compounds, and perfluoroalkyl substances (PFASs), thereby acting as potent vectors for toxic contaminants, pathogens, and antibiotic resistance genes [8,9]. Besides altering soil physicochemical characteristics, MPs exert deleterious impacts on soil fauna (e.g., earthworms, nematodes, mites, springtails, snails, and soil insects), which are indispensable for maintaining soil health and ecosystem functioning. MP ingestion by these organisms has been associated with growth inhibition, reproductive dysfunction, oxidative stress, intestinal injury, gut microbiota dysbiosis, and mortality, thereby disrupting nutrient dynamics and ecological equilibrium [10,11].

MPs profoundly interfere with soil biological functioning by reshaping microbiota structure, ecological interaction networks, and biogeochemical processes across soil-plant systems. Conventional and biodegradable MPs disrupt microbial diversity, plastisphere enrichment, and suppress nutrient mineralization, ultimately impairing overall soil quality and functionality [12]. These MP-mediated alterations in microbial communities and plant stress pathways subsequently influence crop productivity, physiological functioning and biochemical responses. Experimental studies reveal that polyethylene terephthalate (PET) fibres markedly impair crop health, reducing root growth, biomass accumulation, and photosynthetic efficiency, while aged nanoplastics were detected in vascular tissues of roots, stems, and leaves, indicating their translocation within plants and possible entry into the food chain [13]. Despite being advanced as sustainable alternatives, PBS- and PBAT-derived MPs trigger xylem blockage, and inhibit photosynthetic rates by 28-74%, and disrupt microbiome-mediated nutrient transformation, highlighting trade-offs between biodegradability and environmental safety [14].

Groundwater environments are also increasingly threatened by MP contamination. A global assessment of 386 groundwater samples identified microplastic contamination across both open groundwater systems (springs and caves) and closed groundwater systems (aquifers and wells), with median concentrations of 4.4 and 2.5 items/L, respectively [15]. Fibres and fragments dominated MP morphology, while polypropylene (PP), polyamide (PA), polyethylene terephthalate (PET), and polyethylene (PE) collectively accounted for nearly 84% of detected polymer types, highlighting the persistence and mobility of MPs across subsoil environments [15]**.** The ubiquitous dispersion of MPs in soil and hydrological networks exacerbates the possibility of their filtration into agricultural produce and livestock, subsequently entering human food chains.

Beyond ecological impacts, MPs and NPs are increasingly recognized as pollutants of emerging concern, with direct consequences for human health. Humans are exposed to MPs through contaminated food, drinking water, inhalation, dermal contact, and medical applications, wherein bottled water may contain up to 5.42×10^7 MP/L and indoor air concentrations range between 0.4 and 59 fibres/m^3 [16]. Once internalized, these microparticulate can permeate biological barriers such as the intestinal epithelium, blood-brain barrier, and placenta, accumulating in organs such as the liver, kidneys, and spleen. Exposure to MPs has been associated with oxidative stress, inflammation, endocrine disruption, mitochondrial dysfunction, and DNA damage, while MPs additionally act as vehicles for toxic contaminants including heavy metals, antibiotics, and bisphenol compounds [16].

Projections indicate that by 2060, microplastic debris will comprise nearly 13.2% of all global plastic waste [17]. Terrestrial environments, particularly agricultural fields, urban spaces, open dumping sites, and industrial districts, are expected to endure microplastic loads up to 23 times greater than marine environments [18]. However, the extent of this accumulation fluctuates substantially across distinct land-use types, influenced by human activities, waste disposal practices, and environmental factors. These trends highlight the urgent need for sustainable management strategies, benign substitutes for synthetic polymers, and scientifically informed policy interventions to curb further environmental deterioration. While previous reviews have largely focused on individual aspects of microplastic contamination, including sources, ecological impacts, or remediation strategies, an integrated understanding linking soil health degradation, plant-microbe interactions, soil fauna, groundwater contamination, food-chain transfer, biodegradable plastics, and policy dimensions within agroecosystems remains limited. Therefore, this review provides a multidimensional synthesis of MP accumulation in agroecosystems, by integrating source-oriented pathways, ecological interactions, sustainability risks, mitigation approaches, and emerging global governance frameworks within an agroecological perspective.

2. Literature search and methodology

This study integrates current knowledge on microplastic contamination in terrestrial and agricultural ecosystems using peer-reviewed research articles, review papers, policy reports, and international regulations published mainly from 2015 to 2026. The literature sources related to the topic were sourced from various scientific databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Some of the keywords used to search the literature include “microplastics in agriculture”, “soil microplastics”, “agricultural plastics”, “wastewater irrigation”, “biosolids”, “polymer-coated fertilizer”, “microplastic remediation”, “circular economy”, and “microplastic policy”.

Research studies that addressed agricultural and terrestrial ecosystems, sources and pathways of microplastics, impacts of microplastics on soil and ecosystems, remediation technologies, waste management practices, and policies were given priority. Experiments as well as field studies were included in the review to obtain a more comprehensive view of the behaviour and mitigation measures associated with microplastics. Literature that had no relevance to agricultural systems and those that provided inadequate methodology information were not included in the review.

3. Sources and pathways of MPs in agricultural systems

Microplastics (MPs) reach agricultural fields through both direct and indirect pathways. Primary MPs are intentionally manufactured as small particles used in products such as personal care items and industrial coatings, whereas secondary MPs are formed when larger plastic debris gradually fragments under UV radiation, friction, wind, and fluctuating temperatures. Major sources, pathways, polymer types and associated environmental risks of microplastic contamination in agricultural soils are summarized in Table 1 (Fig. 1).

3.1. Plastic film mulch and shade nets

Plastic mulch films and shade nets are significant sources of MP pollution and PAE contamination of soils [39]. These inputs typically consist of polymers such as LDPE, PE, PP, HDPE, PVC and sometimes blends with biodegradable polymers. While they modify crop microclimates and optimizing resources, they have long-term environmental impacts. The fragments form through combination of photochemical, mechanical and thermal degradations. Solar radiation varies from the UV range (290-400 nm) through visible up to infrared (400-2500 nm), which induce photo and thermos-oxidation, weakening polymer chains over time [40,41]. Consequently, degradation affects thin films more than thicker ones, leading to embrittlement, cracking and accelerates MP release into soil. The surface roughness and porosity of LDPE increase with aging, thereby facilitating easier disintegration [42–44]. Thus, even in protected environments, where weathering is limited, the excess plastic film will generally not be removed but will rather remain in the environment and increase cumulative loads of MPs [7].

Similarly, shade nets are fibrous polymeric structures that degrade under environmental stress. When plastics fragment, they release fibrous microplastics into the soil and irrigation water, facilitating the entry of plastic pollutants into agroecosystems [41]. A second source of concern involves additives, particularly phthalate esters such as butyl benzyl phthalate (BBP), leaking from a polymer matrix due to the absence of strong binding [45–47]. The presence of remnants from mulch films and shade netting materials in soil indicates that agricultural plastics will progressively become more of a persistent source of MP and additive pollution rather than being used transiently as agronomic tools.

3.2. Drip irrigation tubes & pipe

Drip irrigation, one of the foundations of modern agricultural field in efficient use of water, notably stands out as a significant yet overlooked source of microplastic pollutants. With the passage of time, the constant flow of water within the pipes and external effects of sunlight and air result in erosion, reducing particle size and facilitating release of microplastics into irrigation systems. Mechanical stress in weak points, particularly where PET and HDPE caps meet, causes wear in material and eventual breakage. PPR, PVC and PE pipes eventually develop rough outer surfaces due to aging. Not only microplastics but also some organic compounds are released [48]. More rigid polymers result in fewer microplastic particles, but these particles are normally larger in diameter [49]. MPs frequently serve as reactive surface in terrestrial and aquatic ecosystems, promoting the adherence of agrochemicals and other trace contaminants. Resultantly, there is rapid deterioration of irrigation water quality. Increase in particulate and mineral-associated organic carbon due to MPs further escalate turbidity in irrigation water and intensify chlorine decay, as a consequence the water treatment process slows down and simultaneously disturb microbial biomass carbon and microbial biomass nitrogen [50]. Continuous deterioration of irrigation infrastructure therefore transforms water delivery systems from passive transport channels into prolific contributor of MP dissemination and irrigation water quality degradation within agroecosystems.

3.3. Polymer coated fertilizers and organic amendments

With the progressive adoption of precision farming, fertilizers that gradually release nutrients according to plant demand are becoming more common. These fertilizers are coated with polymeric materials such as polyethylene, acrylic films, and polyurethane, which eventually disintegrate into small particles because of their limited degradability in soil. Eventually, this contributes to an already burdened soil with more microplastic particles [51]. The unused, empty polymer shells are left in the soil, while the nutrients are released slowly, which can be considered as a “hidden source of plastic pollution” [52]. The mechanical forces of soil abrasion, raindrop impact, tillage, and even livestock trampling can accelerate the degradation of such materials. These forces cause micro-cutting and micro-ploughing, which can help degrade the materials physically [30]. Moreover, UV exposure can further accelerate the degradation of the materials due to photodegradation, resulting in material loss, reduced coating thickness and loss of strength (Fig. 2) [53].

Besides polymer coated fertilizers, organic fertilizers and manure-based composts are increasingly recognized as important secondary sources of microplastics (MPs) in agricultural soils. [23] detected 100% presence of MPs in commercial organic fertilizers, ranging in abundance from 760 to 9454 items g^{-1} and dominated by highly fragmented small-size MPs that are highly mobile in the environment. Fertilizer MPs abundance was positively associated with several fertilizer attributes, including pH, available potassium concentration, and heavy metal contamination, whereas frequent fertilization with organic fertilizers resulted in greater MP accumulation due to favourable soil temperatures and moisture content. Additionally [54], observed considerable contamination with MPs in commercial organic fertilizers and farm composts, estimated to range between 4266.7 ± 2274.5 and 18, 028.6 ± 2000.0 items kg^{-1}. Farm compost and animal manure-based fertilizers showed higher MP contamination owing to uncontrolled composting, domestic and traffic runoff, and airborne pollutants. Most observed MPs were small (less than 1 and 3 mm), indicating higher environmental transportability and biological risks, while fibers comprised the dominant form of MPs, and polypropylene (PP) and polyethylene (PE) prevailed among polymers. These findings suggest that agricultural fertilizers and organic amendments may function as continuous sources of MPs capable of altering the long-term physical and chemical stability of soils through repeated deposition of mobile plastic particles. The predominance of small, highly mobile, and fragmented MPs in these amendments increases the potential environmental mobility, persistence, and interactions with biogeochemical soil cycles. Additionally, the association of MPs with heavy metals and other contaminants from fertilizers implies that repeated application of fertilizers could cause cumulative ecological stress on agroecosystems through various means besides conventional nutrient loading.

3.4. Sewage sludge and wastewater irrigation

Wastewater treatment plants (WWTPs) are major sources and sinks of MPs, mainly due to MP accumulation in sludges during treatment processes [55]. Additionally, centralized and decentralized WWTPs release MPs of varying sizes. Larger MPs (1000-5000 μm) are mainly released from centralized WWTPs owing to differences in shear stress and breakdown mechanisms during treatment, whereas smaller MPs (50-1000 μm) are more common in decentralized WWTPs due to longer activated sludge retention times and enhanced fragmentation [56]. Secondary plastic particulates such as fibers, films, and fragments represent the dominant contaminants in biosolids and treated wastewater, while primary MPs, including microbeads from household detergents, are comparatively less prevalent [57].

Despite advanced treatment, MP residues persist in biosolids, which are frequently applied to agricultural fields due to their significant fertilizer value, typically containing N (2.35 to 4.2%) P_2O_5 (2.46 to 3.2%), and K_2O (0.83 to 1.24%) [58]. Ash from burned sludge may contain

Table 1
Major sources, pathways, and environmental risks of microplastic contamination in terrestrial and agricultural ecosystems.

Sources	Estimated contribution	Dominant polymer	MP type and size	Primary/ Secondary source	Pathway	Associated contaminants/Risks	Region	Reference
WWTP-derived agricultural inputs (sewage sludge, biosolids, wastewater irrigation)	617-936 MP/g dry solids; 993 MP/kg sludge reported in WWTP sludge	PP and PE (dominant). PES, PET, PVC, PU, PVA	Fibres (dominant). Fragments. films, pellets and beads (fine MPs <100 µm; commonly 1-3 mm)	Secondary	Land application of WWTP sludge/ biosolids and environmental discharge from wastewater treatment systems	High ecological risks, contaminant transport, soil and groundwater contamination, potential trophic transfer	India, Ghana	[19,20]
Conventional and biodegradable mulch film	5.5×10^3 to 4.9×10^4 items kg^{-1} soil; residual plastic film fragments averaged 15.4 kg ha^{-1} and reached 155 kg ha^{-1}	PE, PP, polyester, polyurethane, polystyrene, starch-PBAT blend	Fragments and films (20-100 µm dominant; $D50 = 67$; MPs commonly 149-200 µm)	Secondary	In-field weathering, fragmentation, and degradation of residual mulch films in agricultural soils	Soil physicochemical alteration, disturbs microbial activity, reduced earthworm reproduction, contaminant transport, groundwater contamination, food-chain transfer	China, Europe	[21,22]
Organic amendments (compost/ digestate/ manure)	34-160 particles g^{-1} dw; 8714–14,219 items kg^{-1} in organic fertilizers; estimated annual input up to 2.75×10^{16} particles to agricultural soils	PP, PE, PET/ Polyester, PVC, Polyurethane, PS	Fibres (dominant), fragments, films, beads and small-Sized MPs (<1 mm dominant; 100-5000 µm)	Secondary	Land application of composts, digestates and manure-based organic fertilizers leading to accumulation and vertical migration of MPs in agricultural soils	Heavy metal adsorption and accumulation, contaminant transport, antimicrobial resistance transfer, soil biota disruption, reduced soil health and long-term ecological risks	Scotland, China, Pakistan	[23–25]
Atmospheric deposition	87-75,421 particles m^{-2} day^{-1}; average deposition rate 7301 particles m^{-2} day^{-1}; forest soil concentrations ranged 120-13,300 particles kg^{-1}	Rayon fibre (32%), PP, PE, PET, PA, PU, PS, PVC, EVAc, PMMA	Fibres (dominant), fragments and films; MPs mainly,50-250 µm; overall size range 3.23-2645 µm	Secondary	Wet and dry atmospheric deposition, rainfall-mediated fallout, long-range atmospheric transport, canopy trapping, litterfall transfer and wind-driven redistribution	Diffuse terrestrial contamination, soil accumulation, disruption of soil physicochemical and biogeochemical processes, microbial and plant impacts, long-distance pollutant transport	China, Germany	[26,27]
Greenhouse plastic films and drip irrigation systems	16.5 ± 2.4 pcs kg^{-1} dry soil; MP accounted for 41.9% of extracted plastics; GF-derived plastics contributed 89.7%; MPs migrated up to 15-20 cm soil depth after 16 weeks under drip irrigation	PE, PVC, PS, ABS	Fragments. Films, and MPs of 0.05-2 mm; micro-, meso-, macro-, and mega plastics detected	Secondary	Fragmentation and weathering of greenhouse films and drip irrigation pipes/ tubes under UV exposure, abrasion, and long-term agricultural use, followed by vertical transport through soil	Soil and groundwater contamination, altered soil structure and porosity, reduced microbial activity and soil fertility, contaminant transport, ecological disruption and potential food-chain transfer	Turkey, Morocco	[28,29]
Polymer-coated controlled-release fertilizers (PC-CRFs)	6 ± 1.6 MP g^{-1} released in water; 72 ± 8 MP g^{-1} released in soil columns; microcapsule accumulation ranged 6-369 mg kg^{-1} in paddy soils; beach accumulation reached 18.1 ± 21.9 kg ha^{-1} along Sea of Japan coast and 6.3 ± 7.9 kg ha^{-1} along pacific coast	PE, PU, alkyd resin, PE-vinyl acetate	Spherical capsules, fragments, and microcapsules; original capsule size generally 3-6 mm	Mainly Secondary	Nutrient-release induced cracking, wet-dry cycles, soil abrasion, irrigation runoff, river transport, direct drainage from paddy fields, tidal/wave redistribution and offshore transport	Long-term Soil and sediment accumulation, groundwater and marine contamination, adsorption of Fe, Al, Zn, Cu, Cr, Ni and other pollutants; Oxidative degradation, ecological disruption, potential plant uptake and food-chain transfer	USA, Japan	[30,31]

(*continued on next page*)

Table 1 (*continued*)

Sources	Estimated contribution	Dominant polymer	MP type and size	Primary/ Secondary source	Pathway	Associated contaminants/Risks	Region	Reference
Textile-derived microplastics and microfibres (home laundering, textile wear, atmospheric and wastewater release)	4.92-13.03 mg microfibre release per 576 cm^2 fabric; 175-560 fibres g^{-1} or 30,000–465,000 fibres m^{-2} released from garments; ~35% (2-13 million tons annually) of oceans MPs linked to textile laundering	PE. Acrylic, cotton, viscose, nylon, PET and blended fibres	Microfibers (<5 mm), nano plastics (<1 μm), fibres and fragments	Primarily primary MPs	Mechanical abrasion during laundering and textile wear, detergent interaction, atmospheric fallout, wastewater discharge, WWTP overflow/sludge transfer, and aquatic transport	Aquatic and terrestrial contamination, food-chain transfer, oxidative stress, endocrine transfer, gastrointestinal and immune effects, microbial transport bioaccumulation and human exposure through seafood, water, air, and food	Bangladesh; global aquatic and terrestrial systems	[32,33]
Urban littering	Cigarette butts constituted ~62% of urban litter; Urban CB density reached 0.19 ± 0.17 CBs m^{-2} with severe pollutant leakage (CBPI-15.4 ± 11.5); paint-derived MPs reached up to 13.600 particles kg^{-1} dry sediment	Cellulose acetate fibres, epoxy resins, PES, PU, PS, acrylics, alkyd resins, PMMA, PET, PVC	Microfibres, paint, flakes, fragments, anti-fouling particles and fragmented MPs (<5 mm)	Both primary and secondary MPs	Improper littering, weathering of cigarette filters and urban paint coating, abrasion, hydro blasting, urban runoff, atmospheric deposition, drainage-system transport and fragmentation	Release of >7000 toxic compound including nicotine, PAHs, heavy metals (Cu, Zn, Cr, Cd, Ni, Pb), BPA/BPF, Oxidative stress, endocrine disruption, neurotoxicity, ecological toxicity, soil and aquatic contamination, pathogen transport, trophic transfer and food-chain contamination	Iran, Brazil, Sweden, Denmark, UK, China, Japan, South Africa, Antarctica	[34–36]
Landfill leachates, municipal solid waste dumpsites, and open dumping systems	MPs ranged from 0.42 to 24.57 items L^{-1}, 10^2-10^4 particles L^{-1}, and 0.16-33,213 items L^{-1} in landfill leachate; adjacent groundwater contained 2-80 item L^{-1}	PP, PE, PET, PS, PVS, PU, Nylon, PMMA and mixed plastic residues	Fibres, fragments, films, flakes, microbeads, and MPs <5 mm; larger MPs >1000 μM also detected	Mainly secondary MPs	Plastic waste weathering, landfill degradation, leachates generation, infiltration into soil and groundwater, surface runoff, atmospheric transport, and waste fragmentation	PFAS, POPs, PPCPs, PAHs, PCBs, phthalates, heavy metals, endocrine disrupters, ecological toxicity, groundwater contamination, bioaccumulation, microbial disruption, and food-chain transfer	China, India, Iran, Indonesia, Thailand, Sri Lanka, Sweden, Nordic countries and global landfill systems	[37,38]

elevated levels of plant nutrients, reaching 13.6% P_2O_5 and 2.7% K_2O. Although biosolids are commonly applied as agricultural amendments, they simultaneously introduce MPs and associated pollutants such as heavy metals, persistent organic pollutants (POPs), and biological contaminants into the soil matrix. Sewage sludge reportedly contains 4196 to 15,385 MP particles/kg [59,60]. Approximately half of sewage sludge is used as fertilizer in developed regions such as Europe and North America [61,62]. In Europe, agricultural lands receive between 125 and 850 tons of MPs per million people annually [61]. Utilizing untreated wastewater intensifies MP accumulation in agricultural soils. In rapidly industrializing Asian countries, notably China and India, untreated or partially treated wastewater is extensively used for irrigation because of rapid urbanization, water scarcity, and underdeveloped sanitation networks [63,64]. Sludge application to land annually releases nearly 0.156 million tons of MPs into the environment in China alone [65]. The current findings robustly demonstrate that WWTPs act not just as partial removal units but also as significant secondary distribution centers for MPs in agricultural ecosystems via the practice of biosolid spreading and wastewater irrigation. The presence of predominantly small-sized and highly fragmented MPs in the treated sewage is concerning due to their enhanced mobility, bioavailability, and persistence in soils. In addition, the association of MPs with heavy metals, POPs, and biological pathogens implies that biosolid-related pollution poses a cumulative threat in addition to plastic pollution, especially in water-stressed ecosystems.

3.5. *Textile fibres*

Synthetic fabrics continuously shed fibrous microplastics throughout their entire lifecycle, ranging from initial manufacturing and daily wear to routine domestic laundering and post-disposal fragmentation. While natural cellulose- and protein-derived fibers deteriorate swiftly with relatively minimal long-term ecological risks, synthetic textiles exhibit remarkable longevity due to their highly oriented and crystallized thermoplastic fibrillar structures formed during spinning and stabilization processes. These durable microfibrillar architectures enhance fiber strength and resilience to weathering, resulting in continuous fragmentation and accumulation of fibrous microplastics across terrestrial, freshwater, and atmospheric environments [66].

Prolonged ultraviolet photodegradation substantially accelerates the release and fragmentation of textile-derived microplastic fibers (MPFs), with responses strongly influenced by fiber diameter and fabric architecture [67]. Plain filament fabrics composed of micro-denier fibers (7.5–7.9 μm) generated the highest MPF shedding after 60 days of UV exposure (~330,000 MPF g^{-1} fabric), whereas interlocked fabrics with coarser fibers (11.7–13.4 μm) exhibited the lowest release. Thinner and shorter fibers enhanced surface exposure and fragmentation potential, accelerating the greater release of lighter and highly mobile MPFs. Additionally, UV weathering yielded fragmented “split MPFs” (8-14% of regular MPFs), thin irregular fibers, and non-fibrous “odd MPs,”

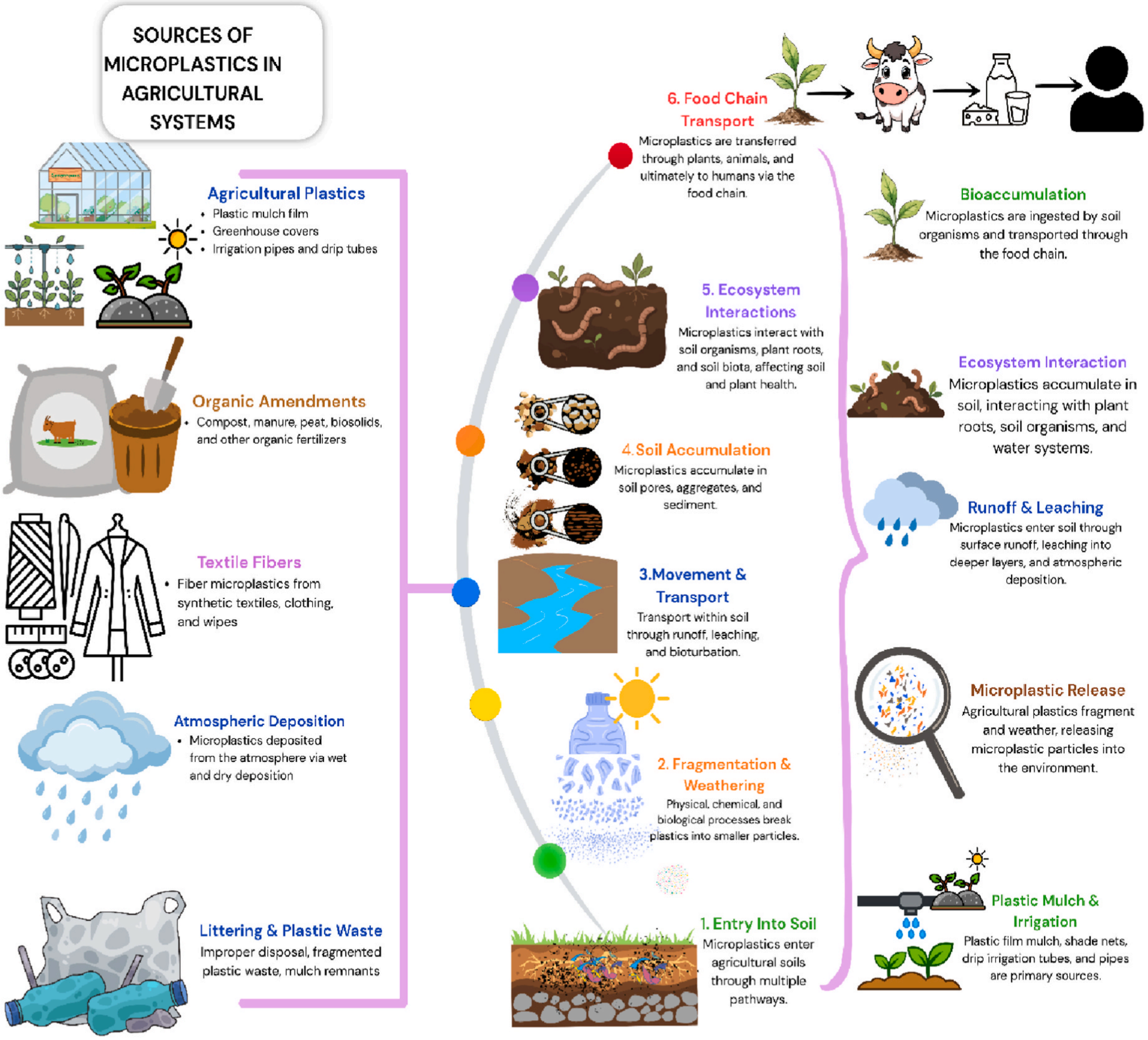

Fig. 1. Diagrammatic representation of the primary sources, transport routes, and environmental interactions of microplastics within agricultural systems. The schematic shows how agricultural plastic waste, organic additives, fabric fibres, atmospheric deposition, and urban littering play significant roles in the introduction of microplastics into soils. The diagram also elucidates the process of degradation of plastic material with subsequent transport via processes of runoff, leaching, and bioturbation. Subsequently, the interaction between microplastics and soil biology, plant root systems, and aquatic systems is depicted along with their role in bioaccumulation and trophic interactions.

indicating progressive polymer degradation and secondary fragmentation [67]. Concurrently, weathering transformed smooth fiber ends into serrated and splintered structures while reducing median fiber length owing to fragmentation. UV-induced polymer degradation increased fiber brittleness and surface cracking, whereas mechanical agitation accelerated fragmentation through surface ablation processes. Similarly [68], reported substantial atmospheric deposition of textile-derived MPs around textile manufacturing facilities, with deposition rates outside factories ranging from 19.3×10^3 to 72.7×10^3 MP m^{-2} day^{-1} and averaging 40.2×10^3 MP m^{-2} day^{-1}. Larger fibers (100-180 μm) were dominant within factory premises, whereas smaller fibers (<100 μm) were more abundant outside, indicating that fine fibers are efficiently transported over greater distances, driven by lower settling velocity and higher wind susceptibility. Taken together, these findings demonstrate that textile MPs are influenced not only by polymer type but also by fiber shape, fabric structure, weathering degree, and atmospheric transport, which regulate their fragmentation, longevity, and distribution properties. The higher dispersibility of weathered fibers also indicates that textile-derived MPs are crucial vectors in widespread airborne dissemination and subsequent contamination of terrestrial and aquatic environments. Thus, the results underscore that polymer structure, textile properties, and environmental aging are critical factors in evaluating the ecotoxicological risks of textile microplastics.

3.6. *Atmospheric deposition*

Atmospheric transport and deposition are major pathways for the redistribution of microplastics (MPs) across terrestrial and aquatic ecosystems. Owing to their submicron dimensions and low density, fibrous and fine MPs remain suspended in the atmosphere for prolonged periods, facilitating widespread atmospheric transport and deposition even in secluded environments. Elevated atmospheric MP deposition flux was documented across South African metropolitan areas compared to rural and forest ecosystems, reflecting the impact of traffic emissions, industrialization, waste disposal, and urban activities [69]. Transparent fibres predominated among the deposited MPs, while PET, PE, PP, and PS indicated substantial contributions from textiles, packaging materials, vehicular emissions, and plastic waste fragmentation. Similarly [70], found an average deposition of 75.4 ± 29.2 particles/m^2 per day and an annual contribution of 1.94 trillion MPs in a coastal bay

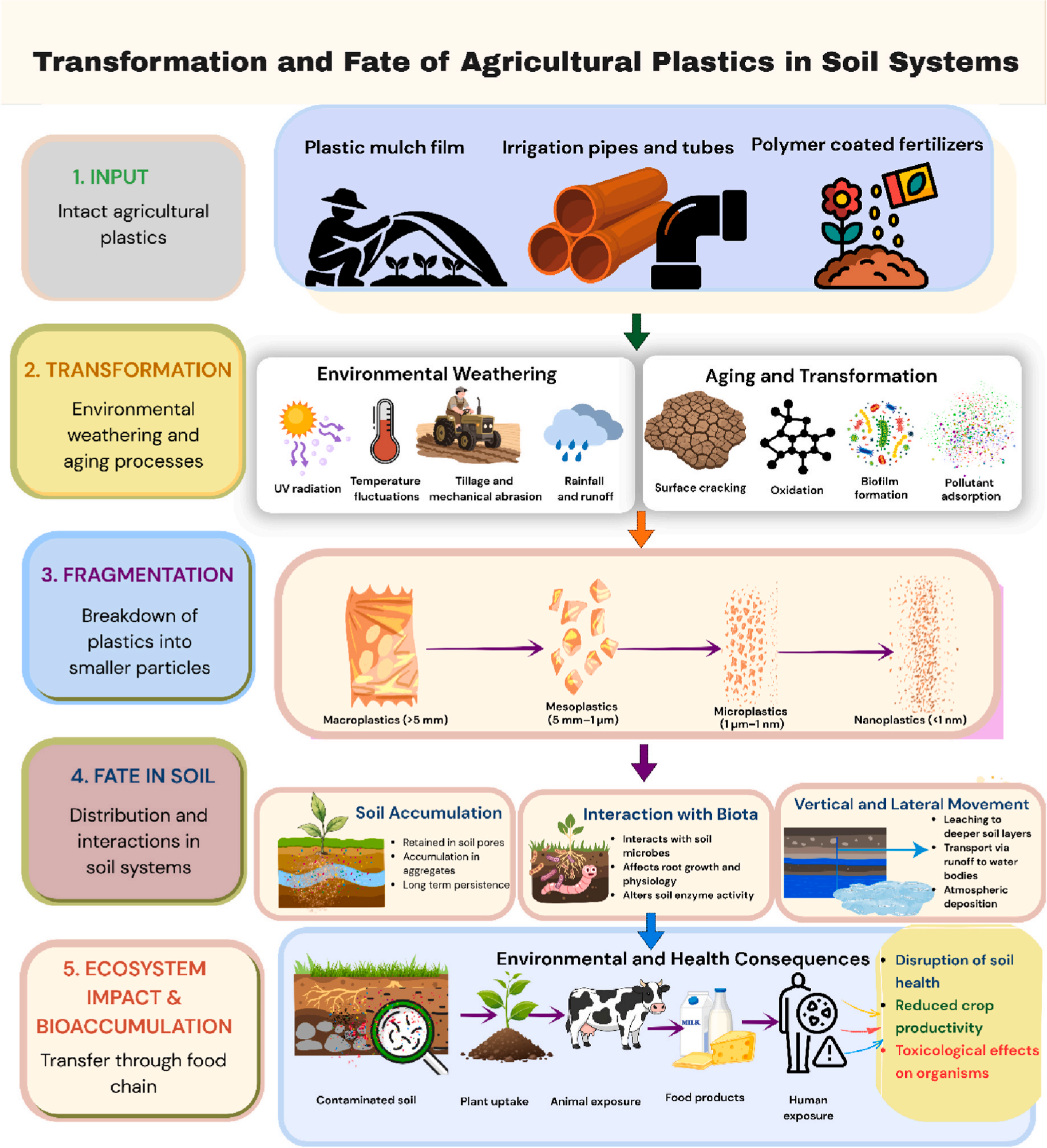

Fig. 2. Schematic representation illustrates the transformation and environmental fate of agricultural plastics in the soil system. Agricultural plastic such as mulching films, drip irrigation pipes and coated polymers fertilizers experiences environmental weathering due to UV radiation, temperature variations, tillage, friction and rain water. This eventually leads to breakdown of the plastics into micro-plastic and nano-plastic that remain in soil and interact with soil flora and roots of the plants. The schematic further indicates the movement of these particles by leaching and runoff process leading to accumulation, degradation and risks to human health.

ecosystem. The deposition pattern displayed marked seasonality, being higher in spring and winter when the prevailing winds came from inland regions and lower in summer when the winds came from the oceans. Furthermore, a direct correlation between MPs and PM2.5 demonstrated the significant contribution of urban anthropogenic emissions to airborne MP pollution. Atmospheric conditions such as precipitation, temperature, air currents, and turbulence strongly influence MP suspension, transport, and deposition processes, highlighting the role of atmospheric fallout in long-range MP dispersal and subsequent environmental contamination.

3.7. *Urban littering*

Poor efficiency of urban cleaning services and prolonged persistence of litter in public spaces have made urban litter a major dispersed source of microplastic (MP) contamination. In Khuzestan province, Iran, litter density ranged from 0.0001 to 0.6502 pieces/m^2, with primary and secondary MPs associated with littering estimated at 47,207–62,767 μg/m^2 and 2127–3140 μg/m^2, respectively, while primary MPs generated through littering amounted to nearly 150 g/year, highlighting improper disposal of cigarette butts and plastic wastes as major contributors to urban MP pollution [34]. Discarded plastic packaging materials are additional important sources of MPs in food products. Polyethylene terephthalate (PET) was identified as the dominant polymer in plastic-wrapped candies, where fiber-shaped MPs constituted 70.13% of detected particles, while processed packaged milk contained 37.78 ± 3.87 to 71.11 ± 10.18 microplastics/L, nearly four times higher than farm-fresh milk, with low-density polyethylene (LDPE) primarily originating from packaging materials [71].

Paint fragments, antifouling coatings, and personal care and cosmetic products (PCCPs) further contribute to MP pollution. Paint particles from weathered architectural, marine, and traffic coatings infiltrate ecosystems via atmospheric transport, runoff, and wastewater, whereas in-water cleaning of antifouling coatings directly releases MPs and biocides into seawater [35,72]. PCCPs containing intentionally added MPs, particularly acrylate copolymers and dimethicone polymers, are also significant primary sources, with approximately 21.4 trillion MP particles estimated to be released annually into the environment [73]. Altogether, these studies reveal that urban activities and consumer-based products constitute ongoing and interconnected sources of MPs, enabling their continuous entry into ecosystems through littering, atmospheric deposition, waste disposal, and degradation of artificial materials. Moreover, the variety of polymer types and different contamination routes suggest that MP pollution in urban areas is not limited only to visible plastic litter but rather is associated with inefficient waste management and the regulation of secondary MP formation.

4. Impact of microplastics on soil and ecosystem health

4.1. Physical soil properties

Microplastics (MPs) cause small but cumulative changes in the physical properties of soil (Fig. 3). The size and direction of these changes depend on the type of MP, its concentration, and the texture of

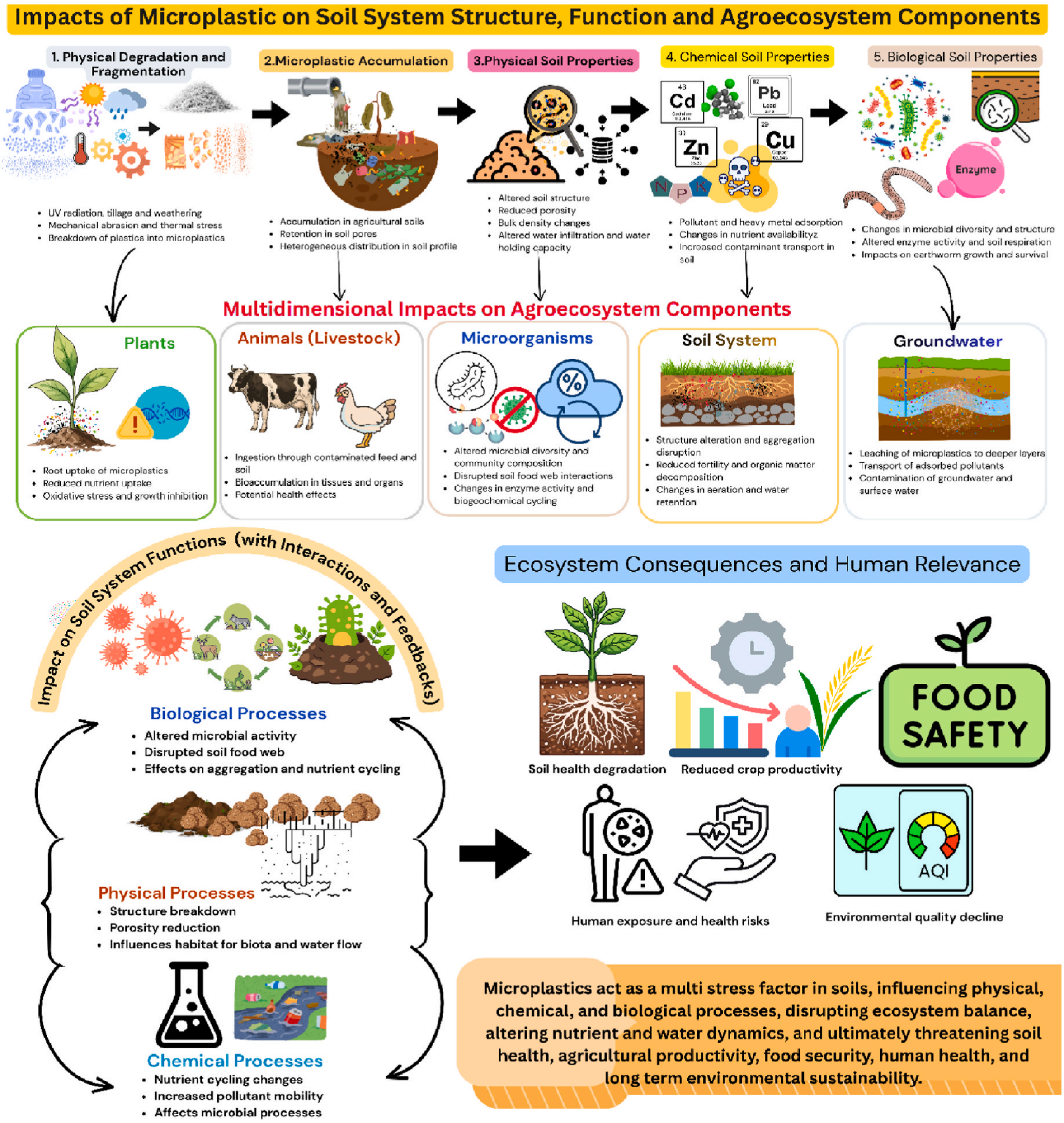

Fig. 3. It represents the multivariate effects of microplastics on soil health and ecosystem well-being. The diagram shows the effect of plastic degradation and decomposition resulting in the build-up of microplastics in farmland soils, ultimately resulting in changes to soil characteristics such as its physical, chemical, and biological characteristics. Such changes can cause alteration in soil aggregation, porosity, nutrient cycle, microbial processes, enzymes, and toxicity of soil contaminants. It is further noted how the impact of microplastics cascade in different agroecosystems ultimately leading to low productivity, environmental degradation, food security threats, and threats to human health.

the soil. Reportedly, at lower levels of polyester-based MPs contamination (0.1-0.4%), bulk density (BD) decreases, which sequentially increases the permeability of air, water, and roots in heavy soils like vertisols [74–76]. The responses differ according to soil type, with sandy loam showing a greater reduction in BD than clay loam soil due to differences in pore size and its porosity [77–79]. There is a linear association between increasing MP concentration in sandy soil and subsequent rise in porosity and water-holding capacity (WHC) attributed to increased micropore development [75], up to a certain threshold level (>1%), beyond which the effect reverses. MP levels greater than 1% tend to encase soil particles, alter pore size and reduce soil adhesion, which is often termed the “wrapping effect” [80,81]. Larger MPs (>1 mm) can block macropores, reducing water permeability whereas smaller size MPs (25 μm) can block micropores, reducing soil aeration and water retention [82]. These changes profoundly disrupt the interconnected soil pore network, especially in polyethylene glycol-derived MPs, causing hampered solute transport, reduced percolation, and perturbed water flow routes, thereby accelerating surface runoff potential and intensifying erosion hazards, notably in sandy soils with MP levels greater than 15% [83,84]. This indicates that the impact of MPs on soil physical properties is governed by concentration, particle size, and soil texture, with low concentrations sometimes favoring soil pores but higher concentrations increasingly perturbing soil aggregation and water flow dynamics.

4.2. Chemical soil properties

The impact of MPs on soil chemical properties is influenced by polymer type, environment, and exposure duration. HDPE and PLA at 1% and 10% increase soil pH [85]. However, low concentrations of aliphatic polyester MPs decrease soil pH due to polylactic acid release during disintegration [86]. In unfertilized soil with MP < 0.03 mm, soil pH decreases, but no changes occur in soil fertilized with organic and inorganic nutrients [87]. Soil pH is higher in soil amended with polymers like PA, PC, PE, PES, PET, PP, PS, and PU [88]. Chemicals released during MP aging and increased surface reactivity alter protons (H^+) exchange with soil water, influencing soil microbial communities and enzymes [89]. Beyond pH, electrical conductivity affects nutrient availability. Lower MP concentrations (PE, PET, PA, mixed) (0.2%, w/w) decrease soil EC, but at 1% w/w, EC declines in both contaminated and uncontaminated soil [8,90]. The effect on CEC depends on polymer types. MPs' hydrophobic nature reduces CEC and nutrient absorption by coating soil particles, affecting ion attraction [91]. Polypropylene (PP) at 0.1% and 0.3% increases soil CEC, while 1% PVC treatment shows contrasting results due to minimal TOC changes, as PP has more carbon content (85.7%) than PVC (38.4%) [88]. Smaller MPs (20 μm) increase CEC more than larger MPs (200 μm) [74]. Smaller MPs like PET 10 are more transportable within soil pores, increasing reactive surface area compared to larger MPs (PET 200 μm) [92]. As MP concentration increases, C, N, K, and micronutrients like Fe, Mn, and Cu decrease due to dilution, while MPs enhance available Zn [93]. MPs increase particulate organic carbon and mineral-associated organic carbon pools, decreasing microbial biomass carbon and nutrient recycling. Prolonged weathering produces reactive surfaces that adsorb POPs and heavy metals like arsenic, cadmium, nickel, lead, silver, mercury, iron, antimony, manganese [10,94]. Altogether, chemical interaction of MPs is polymer-specific and concentration sensitive, with effect from soil acidification to alkalization and transformed EC and CEC. There is a need to understand that microplastic pollutants do not act as inert particles in the soil but act as active surfaces that can affect heavy metal mobility.

4.3. Biological soil properties

Microplastics (MPs) alter soil microbial communities, macrofauna, and nutrient cycling under both short- and long-term exposure, with effects on microbial biomass, diversity, community structure, and functional stability largely governed by interactions between MPs and soil particles. Biological responses exhibit a bimodal trend, where low MP concentrations temporarily stimulate microbial activity, whereas higher concentrations reduce microbial diversity and stability. At low levels (≤1%), MPs may stimulate microbial activity by increasing nitrogen-fixing and phosphorus-solubilizing bacteria, thereby enhancing nutrient cycling [95,96]. Smaller MPs (13 μm) increase microbial abundance and diversity, while larger MPs (150 μm) at 5% reduce soil heterogeneity [97]. Similarly, LDPE at 7% decreases bacterial multiplicity, whereas 2% LDPE enriches bacterial diversity [96]. Biodegradable MPs containing labile carbon promote synergistic microbial interactions, whereas non-biodegradable MPs with recalcitrant carbon reduce microbial biomass [98,99]. A meta-analysis further revealed that biodegradable MPs reduce bacterial populations, while fungal diversity responses remain variable [100]. MPs also increase plastic-degrading microbial communities such as Bacteroidetes, Actinobacteria, and Proteobacteria on reactive MP surfaces and MP-amended soils [101,102]. MPs alter key soil enzymes involved in carbon, nitrogen, and phosphorus cycling, including phosphatase, N-acetyl glucosaminidase, β-D-glucosidase, and cellobiosidase [103,104]. Phosphatase activity increases at low MP concentrations but declines at higher levels, indicating disruption between enzyme activities and nutrient availability [103,105].

The influence of MPs on fungal communities is strongly moisture-dependent. Under well-watered conditions, MPs reduce pathogens, saprotrophs, mutualists, and overall fungal community richness by 47%, 33%, 45%, and 40%, respectively, while under drought conditions, they increase fungal abundance, likely because of toxicant leaching and improved water-holding capacity [106]. MPs under well-watered conditions also decrease richness of Ascomycota, Basidiomycota, and Chytridiomycota, along with reductions in filamentous fungi and yeast populations [106]. In contrast, fungal genera such as *Aspergillus*, *Fusarium*, and *Penicillium* utilize plastic-derived carbon, promoting proliferation in MP-polluted soils [107]. Arbuscular mycorrhizal fungi (AMF) hyphae, arbuscules, and coils increase in polyester (PES)-amended rhizosphere soil [108]. MPs additionally act as substrates for pathogenic fungi and airborne moulds [109]. The differential responses of the microbial and fungal communities imply that the ecological perturbation induced by MPs is highly context-specific and modulated by polymer type, particle size, density, moisture, and carbon content. These changes in microbial community structure and enzyme activity could gradually affect nutrient cycling and soil ecosystem functioning.

4.4. Plants

Microplastics detrimentally influence crop growth, physiological activity, and rhizosphere microbiome in major crops such as wheat, rice, maize, soybean, and legumes, with PVC exhibiting greater toxicity than PE or PS microplastics. Small and aged MPs exhibit greater toxicity resulting from alterations in their physicochemical properties and leached additives [110]. Smaller MPs together with soil texture were responsible for more significant maize growth attenuation, disturbance in amino acid metabolism, and lignin biosynthesis processes [110]. Larger MPs cause growth suppression owing to their effect on roots, including damage and pore obstruction. Submicron MPs (~0.2 μm) can permeate root tissue and the vascular system, facilitating their trophic transfer through the food chain [111]. PE and PVC MPs reduced SOD activity by 15.35-36.7%, while enhancing POD activity, thus leading to a 17.94-23.81% decrease in photosynthetic rate on account of oxidative stress and metabolic disturbances [112]. Subsequently, PS and PVC MPs caused a reduction in biomass, plant height, photosynthetic rate, stomatal conductance, and SPAD values, while raising malondialdehyde and hydrogen peroxide levels in rice [113]. Additionally, polyethylene MPs suppressed seed germination, seedling growth, root activity, and photosynthetic pigment levels. These effects could be related to rhizosphere disruption, disturbance in root exudation, disturbance in chlorophyll synthesis, and increased oxidative stress. Although MPs stimulate the production of antioxidant enzymes (SOD, POD, and CAT) as an adaptive mechanism, excessive exposure exceeds the plant resistance potential and leads to a decrease in crop productivity. Legumes show accelerated chlorophyll degradation, reduced root nodule numbers, and leghaemoglobin levels [114], whereas low concentrations of PS MPs stimulate leghaemoglobin synthesis, chlorophyll pigment accumulation, and nutrient uptake in cowpeas [115]. Furthermore, combined exposure to MPs with salinity and heat stress reduces biomass, chlorophyll content, nutrient uptake, plant height, root length, and water content in wheat and maize, while increasing oxidative stress and decreasing wheat biomass by up to 75% [116,117]. This indicates that the toxicity caused by MPs in plants is highly dependent on polymer type, size of MPs, interactions between environmental stresses, and crop-specific physiological reactions. The above evidence clearly indicates that the toxicity effects of MPs on plants vary from one species to another, and are greatly affected by the composition of polymers, particle sizes, soil properties, and other forms of environmental stresses. Moreover, the synergy between MPs and salinity/heat stress is likely to indicate that with future climatic stress conditions, MP toxicity on plant physiology could be exacerbated. This could affect agricultural production in contaminated agroecosystems.

4.5. Ground water

Groundwater is a primary source of consumable water, irrigation, and household use globally; however, rising microplastic (MP) contamination threatens aquatic ecosystem impairment and public health. Moreover, MPs also serve as transport vectors for toxic contaminants (e.g.: heavy metals, antibiotics, and persistent organic pollutants) resulting in increased migration and environmental threat to groundwater [118]. Human exposure to such contamination may result from the direct intake of contaminated groundwater or indirectly by means of the food chain that relies on contaminated water resources. Potential health risks linked to microplastics involve physical damage to tissues, exposure to toxic additives, and pathogens transmission [118]. Landfill leachate changes the chemical composition, microbiology, and MP concentration of groundwater, where manganese (Mn) and chromium (Cr) are the most frequent contaminants, while Proteobacteria are the dominant microorganism in the environment [119]. The presence of MPs further alters microbial nitrogen metabolism and the nutrient cycle in coastal aquifers affected by seawater intrusion, promoting denitrification, nitrogen fixation, and ammonia retention, which exacerbates eutrophication threats [120]. MPs act as transport vectors and biogeochemical modulators in coastal systems. These findings suggest that MPs in the groundwater do not act simply as contaminants but as dynamic transport mechanisms that can potentially alter the biogeochemistry, microbial dynamics, and even movement of contaminants within the subsurface environment. The presence of MPs in conjunction with the effects of landfill leachate, agriculture, and the hydrologic cycle illustrates how vulnerable the groundwater system is to MPs.

4.6. Soil fauna

As it is well-known, medium-sized animals like earthworms, mites, and springtails are indispensable in the maintenance of soil quality. Nonetheless, the occurrence of MPs in these important animals poses a significant threat to the agroecosystem functioning [121]. Given that microplastics are minute particles, they can easily be ingested by other minute soil invertebrates like soil insects, nematodes, and snails causing different adverse effects. MPs may have several toxicological effects on the growth, development, lifespan, and survival of soil fauna through a variety of mechanisms including ingestion and bioaccumulation, histopathological alteration, oxidative stress, DNA damage, genotoxicity, reproductive toxicity, neurotoxicity, metabolic alterations, and gut microbiota dysbiosis. Moreover, MPs may interact with other environmental contaminants, resulting in enhanced toxicity to soil biota [122]. Earthworms exposed to MPs have shown toxic responses, which include growth inhibition, intestinal injury, body weight loss, immune system changes, changes in gut microbiome, reproduction impairment, and even death, in severe cases [123,124]. However, the reported impacts are often contradictory and vary depending on the species studied, type of plastic, and exposure concentration. For instance, while exposure of *Lumbricus terrestris* to polyethylene microplastics at concentrations between 0.2 and 1.2% (w/w dry soil) caused growth inhibition and eventually mortality, [123], another study on *Eisenia fetida* showed that there were no observable adverse impacts following exposure to 0.25-0.5% polystyrene microplastics, but growth inhibition occurred at higher than 1% concentration in dry soil [125]. In order to provide a comprehensive evaluation of the impacts of microplastic contamination in soil ecosystems, further studies are recommended to consider different soil fauna.

4.7. Human health

Microplastics pose substantial environmental risks and human health hazards because of their persistence, bioavailability, and bioaccumulation within terrestrial food systems. Microplastic exposure has been linked with irritation of the respiratory system, asthma, obesity, gastrointestinal disorders, and cardiovascular diseases, thereby posing significant risks to human health. MPs mostly contain chemical additives, such as phthalates and bisphenol A (BPA), and they also have the ability to sequester environmental pollutants like heavy metals and persistent organic pollutants [126]. These associated chemicals have been implicated in endocrine disruption and various adverse health outcomes, such as diabetes, cancer, obesity, reproductive disorders, neurological disorders, and immune dysfunction [127,128]. Further research suggests that MPs less than 10 μm are able to penetrate human organs and cell structures [129]. After penetrating the human tissues, MPs have been proven to cause harm through particle toxicity, chemical toxicity, and the ability to act as vectors of pathogens and parasites [130]. MPs are able to transmit harmful bacteria, which result in food poisoning and other diseases [131]. It has been discovered that after ingestion, MPs are able to accumulate in the intestines, triggering inflammation, suppressing endocrine function, and disrupting normal gastrointestinal processes. Moreover, MPs are able to affect the gut microbiota, which causes intestinal microbial imbalance [132]. Moreover, smaller-size MPs also have the ability to pass through the intestinal wall into the bloodstream, allowing them to reach vital organs like the liver, spleen, and lymphoid tissues, thereby creating potential health risks [132,133]. The consumption of MPs via contaminated meat and animal products might negatively affect gastrointestinal metabolism [88,134]. Research conducted on rodents indicates that intake of MPs in foods and drinking water can affect the reproductive system. In male rodents, MP intake caused low testosterone levels, abnormal sperm, testicular atrophy, and increased apoptosis of sperm [135]. MPs have also been found in ovarian granulosa cells, where they were related to apoptosis, pyroptosis, and ovarian fibrosis [136]. Reproductive disorders are mainly caused by oxidative stress and metabolic enzyme activity imbalances resulting from MP exposure [137]. Generally, the increasing evidence implies that MPs are more than just environmental contaminants but biologically active pollutants that may induce multi-organ toxicity, metabolic disorders, microbial dysbiosis, and reproductive disorders as a result of chronic exposure. Nonetheless, the extent of health hazards posed by MPs is still unclear since many existing studies are limited to lab-scale experiments using different particles at various concentrations and exposure conditions. In that regard, additional research over a prolonged period under realistic exposure conditions is necessary.

5. Policy and mitigation strategies

Although global regulations on microplastic (MP) pollution are evolving, they remain inadequate for agricultural and terrestrial systems. Most policies mainly target primary MPs and marine environments, while major land-based sources such as mulch films, irrigation systems, coated fertilizers, sewage sludge, wastewater irrigation, organic amendments, textile fibers, landfill leachates, paints, packaging materials, and personal care products remain poorly regulated.

5.1. Global plastic governance and regulatory frameworks

Addressing the growing concern of plastic pollution, the Basel Convention (1989) adopted the Plastic Waste Amendments in 2019 to strengthen regulations of transboundary movements and management of plastic wastes [138,139]. The amendments categorized mixed and contaminated plastic wastes under the Prior Informed Consent (PIC) procedure, while allowing cleaner and recyclable plastic streams under regulated trade conditions. China's 2018 ban on plastic waste imports, along with stricter import regulations in several Asian countries, substantially reshaped the global plastic waste market, resulting in a 30-41% reduction in market size and major changes in transboundary plastic waste flows. These developments increased international scrutiny on plastic waste shipment and highlighted plastic pollution as a transboundary environmental and environmental justice issue; however, existing regulatory loopholes for diffuse terrestrial and agricultural sources of MPs, including mulch films, sewage sludge, wastewater irrigation, textile fibers, and polymer-coated agrochemicals, hampered effective plastic governance and strengthened the policy relevance of addressing MPs within agricultural systems [140].

Additionally, the United Nations Environment Assembly (UNEA-5.2) adopted Resolution 5/14 in March 2022 to commence negotiations for a legally binding Global Plastics Treaty addressing the entire lifecycle of plastics, from production to usage and disposal [141]. The Intergovernmental Negotiating Committee (INC) has since conducted various negotiation sessions to develop the treaty framework. These ongoing negotiations further highlight the transboundary nature of plastic and microplastic pollution and the need for coordinated international cooperation and harmonized regulatory frameworks for managing plastic pollution across interconnected terrestrial, freshwater, and marine ecosystems [142].

5.2. National and regional regulations on microplastic pollution

5.2.1. European union

The European Strategy for Plastics in a Circular Economy, approved by the European Parliament and disseminated via Communication COM (2018)28, represents a major breakthrough towards more environmentally sustainable plastic use. Some of the primary objectives are to confirm that all plastic packing can be recycled by 2030, to curtail on single-use plastics and to reduce the use of microplastics. The EU Waste Framework Directive (Directive 2008/98/EC) legally supports Extended Producer Responsibility (EPR), which is a crucial element of this strategy. EPR requires producers to handle plastic waste post-use, frequently through Producer Responsibility Organizations (PROs). EPR enforcement throughout member states remains uneven, although it could be highly effective. Only eight of them have fully implemented such systems for agricultural plastics [143].

5.2.2. United States

The Microbead-Free Waters Act (2015) was the first initiative undertaken by the United States took to regulate the use of plastic microbeads in wash-off cosmetics. The law mandated that by 2019, these beads would be prohibited. This was followed by the Save Our Seas Act 2.0 (2020), which gave the U.S. Environmental Protection Agency (EPA) responsibility for defining and monitoring microplastics in food and water systems. However, as of 2022, the federal government had not yet established an official definition. California and several other states have taken the lead by requiring MP monitoring in drinking water and developed standard detection protocols. There isn't a single federal law that enfolds everything, but regulations such as Toxic Substances Control Act (TSCA), the Clean Water Act (CWA), the Safe Drinking Water Act (SDWA) and the Clean Air Act (CAA) provide regulatory approach to manage MPs by categorizing pollutants, doing toxicological evaluations and framing standards for particulate matter [144].

5.2.3. New Zealand

New Zealand has been among the pioneers in having primary MPs. The Waste Minimisation Act of 2008 enables the imposition of taxes on wastes, prohibition of certain products, and implementation of stewardship schemes. The prohibition of microbeads in cosmetic products in 2017 and the phasing out of plastic bags in 2019 are among the most significant developments. Although the Act provides for product stewardship, the implementation remains limited. Low waste disposal charges, limited policy coverage, and overreliance on voluntary compliance have further impeded the enforcement of systemic governance. Current policies are promoting a circular economy approach, but development is hampered by quantitative data limitations and implementation challenges [145].

5.2.4. India

India recently passed the Plastic Waste Management Amendment Rules, 2024, introducing more stringent plastic laws [146]. The new rules permit the manufacturing of carry bags and other plastic products certified as compostable or biodegradable polymers. To be certified as compliant, food-contact polymers must be labelled appropriately and adhere strictly to the criteria established by the Food Safety and Standards Authority of India. Manufacturers must get certification from the Central Pollution Control Board (CPCB) before marketing their products. They are also responsible for managing plastic waste before it reaches consumers and must regularly report to their State Pollution Control Boards (SPCBs) or Pollution Control Committees. These measures aim to strengthen accountability and improve plastic debris management practices.

5.2.5. China

The 2017 ban on plastic trash imports marked the commencement of China's supervisory change, leading to the formation of a circular economy. China's Plastic Pollution Control Action Plan (2021-2025) is based on the Law on Solid Waste Pollution Prevention and Control and the Circular Economy Promotion Law. It mandates the gradual prohibition of imperishable plastics in domains like e-commerce, agriculture and retail [147]. The plan reinforces biodegradable alternatives, improved debris collection and eco-friendly conveyance. The Agricultural Film Recycling Action Plan and the Agricultural Film Management Approach aim to reduce plastic use in farming by advocating closed-loop recycling and biodegradable mulch films, thereby tackling MP pollution at its agricultural source.

The global regulatory response is currently disjointed and primarily microplastic- or marine-centric. Agricultural routes, including mulch films, irrigation schemes and polymer-coated fertilizers, are still inadequately regulated. Although Extended Producer Responsibility (EPR) schemes show promising potential, their implementation remain inconsistent across countries. Furthermore, the lack of systematized terminology, performance auditing systems and threshold values for soil ecological impact undermines regulatory operations. A coordinated approach addressing terrestrial microplastic flux is urgently required to support existing marine-centric regulatory policies.

6. Mitigation strategies

6.1. Adsorption- and filtration-based remediation approaches

6.1.1. Biochar-based immobilization and adsorption of microplastics

Biochar is a promising and sustainable method to reduce microplastic pollution in soils due to its unique physical and chemical properties. Its large surface area, permeable structure, and oxygen-rich functional groups enable electrostatic and hydrophobic interactions with MPs, thereby lowering their transportability and ecotoxicity [100, 103]. Consequently, MPs become trapped in the biochar matrix, limiting their soil movement. Cow dung-derived biochar shows high potential, eliminating up to 92.4% of MPs at pH 9 and maintaining >85% efficacy after seven reuse cycles, demonstrating its stability and economic reusability [148]. Biochar's micropores (1 to 8 μm) allow MPs to become entangled inside. Tortuous pathways further enhance attachment through physical and chemical interactions [47,149].

Beyond physical retention, biochar reduces co-contaminant toxicity. Phosphorus-enriched biochar (PBC) effectively decreased oxidative damage from OTC + PE to pak choy roots, lowering APX activity from 2826 to 1160 U/g and CAT from 174 to 130 U/g. PBC restored CAT activity to 350-443 U/g, APX to 2427-2564 U/g, and SOD to 0.77 U/g, reducing OTC content in plants to 2.79 mg/kg. SBC's maximum adsorption capacity (Qmax) for OTC was 10.87-12.51 mg/g due to its high surface area, π-π bonding sites, and aromaticity [150]. Biochar's adsorption capacity for PLA and PLA + OTC exceeded that for PE and PE + OTC. Microplastics and antibiotics compete on biochar's active sites, thereby reducing biochar-antibiotic interaction [149]. Recent advancements include polymer-coated magnetic activated biochar-zeolite composites for removing polystyrene microplastics [151,152].

All these results indicate the potential of biochar to minimize the mobility and toxicity of MPs as well as to restrict their interaction with other co-contaminants in soil environments. Nevertheless, the majority of these studies are limited to short-term laboratory investigations, and the long-term applicability of biochar is unknown. Therefore, future research must focus on field-scale evaluations and optimization of biochar materials to maximize their efficiency in removing MPs from agricultural soils.

6.1.2. Improved GAC filtration with pre-ozonation

Adding a light ozonation step ahead of GAC (granular activated carbon) filtration greatly enhances microplastic removal. Ozonation changes the physical and chemical properties of the MPs, especially those covered with organic matter, such as by reducing surface charge and breaking up biofilms, which can then be more easily adsorbed onto GAC surface [153,154]. This integrated technique not only improves removal efficiency but also lengthens the lifespan of GAC by reducing fouling and preserving adsorption efficiency. Full-scale GAC-based wastewater treatment plants reported the removal of total solids at 81-87%, indicating strong potential for widespread application. Complementary results by Ref. [155] support the versatility of GAC: a filter of soil-zeolite-GAC removed 65-99% of PAHs from stormwater in 24 h, along with removal efficiency of 94% for iron, 85% for aluminium, 80% for manganese and 64% for zinc. Approximately, 70% of dissolved organic carbon (DOC) was removed by GAC filtration, lowering DOC concentrations to 1.76 mg/L, while over 75% of hydrophobic organics were captured. The remaining hydrophilic fraction consisted of humic substances (52%), building blocks (27%), biopolymers (15%) and low-molecular-weight acids and neutrals (7%). These findings clearly indicates that an ozone-GAC combined system can serve as a multi-functional approach for mitigating MPs, organic pollutants, and metallic contaminants.

6.2. Nanotechnology-enabled remediation strategies

Nanotechnology offers scalable, selective, high-efficiency solutions for microplastic (MP) remediation in aquatic and terrestrial systems. Magnetic separation using functionalized iron-based nanoparticles (FNPs) is particularly promising. FNPs form hetero-aggregates with negatively charged MPs such as multilayer polyethylene (MPE) and multilayer polyethylene terephthalate (MPET) because of their high positive zeta potential in acidic conditions ($pH < 7$) [156]. MPET, with higher surface charge density and more hydrophilic groups, shows stronger attraction to FNPs. Its lower crystallinity further aids nanoparticle adhesion, thereby enhancing aggregation [157]. Optimal aggregation occurs at 0.001-0.005 g/L FNP for MPET and 0.005-0.01 g/L for MPE, facilitating MP removal through magnetic sedimentation. Photocatalytic degradation using semiconductor-based nanomaterials such as titanium dioxide (TiO_2) shows significant MP degradation potential. Interaction between TiO_2 and nano-polystyrene reduced polymer mass by 23.5%, while low-density polyethylene (LDPE) showed an 18.1% weight reduction after 300 h of UV exposure with 50 nm TiO_2 [158]. Reactive oxygen species generated during UV exposure cause oxidation and surface erosion. Biogenic nanoparticles offer an eco-friendly method for MP degradation. Silver nanoparticles from *Aspergillus oryzae* degraded LDPE by 64.5% and HDPE by 44.4% within five weeks, demonstrating biogenic nanomaterials' synergy in accelerating plastic degradation [159].

These results suggest that nanotechnological methods are highly promising because of their high adsorption capacity, catalytic degradation potential, and selective separation capabilities in removing MPs. However, there is an inadequate focus on the stability, recyclability, ecotoxicity, and large-scale environmental application of nanoparticles.

6.3. Biological remediation approach

6.3.1. Phytoremediation of microplastics using aquatic macrophytes

Aquatic macrophytes for phytoremediation is a promising natural approach for reducing microplastics (MP) in freshwater ecosystems. Species like *Thalassia testudinum*, *Lemna minor* and *Fucus vesiculosus* exhibit a high capacity for the uptake of significant amounts of MP, thereby reducing particle mobility and bioavailability to aquatic organisms. The adhesion of particles to leaf surfaces arises from electrostatic attraction, van der Waals forces, hydrogen bonding, micropore filling, and π–π interactions. These interactions involve surface biomolecules such as lignin, cellulose, polysaccharides, lipids and proteins present in plant epidermal tissues [160]. Among aquatic plants, *Eichhornia crassipes*, commonly known as water hyacinth, represents one of the most effective species for the removal of both micro- and nanoplastics (NPs) because of its rapid growth rate and free-floating habit. Under experimental settings, this species achieved removal rates of 66.4% for 20 nm PS-NPs and 44.7% for 200 nm PS-NPs within 48 h [5]. The high removal efficiency is attributed to passive adsorption on its large fibrous root surface area (>150,000 mm^2 per plant). These roots act as the main sites for particle interception, facilitating MP/NP capture without active uptake. Structural anatomy also plays a crucial for MP containment in *E. crassipes*. Root caps were identified as the primary sites of MPs adhesion, while a well-developed “vascular ring” in the stem restricts the movement of MPs to aerial tissues. This acts as an anatomical barrier protecting vita plant regions such as the shoot apical meristem [5]. This indicates that macrophytes in water bodies are effective biological filters that can be used as cost-effective and environmentally friendly MP remediation tools. However, problems concerning long-term retention, biomass disposal, and trophic transfer of MP via food chains still need to be studied.

6.3.2. Enzyme- and microbe-mediated biodegradation of microplastics

Microplastics (MPs) break down through enzymatic degradation in two steps: (i) depolymerization, where extracellular enzymes break down long-chain polymers like low-density polyethylene (LDPE) into oligomers, dimers, and monomers, which microbes can take up; and (ii) mineralization, where these products are further broken down into CO_2,

H_2O, and CH_4, which microbes use as carbon sources. Different enzymes can act on different polymers. For instance, laccase induces pitting and erosion on high-density polyethylene (HDPE) within 90 days. Manganese peroxidase from *Phanerochaete chrysosporium* reduces the molecular weight and tensile strength of polyethylene (PE), making it easier to disintegrate. Similarly, soybean peroxidase alters the chemical nature of PE surfaces by reducing hydrophobicity, thereby making them more easily decomposable by microorganisms and enzymes [161].

P*seudomonas* spp. PVA oxidase decomposes water-soluble polyvinyl alcohol (PVA). This catalysis occurs due to the action of serine hydrolase action and results in the decomposition of β-diketones overlaid polymers into monomers, which can be further decomposed by bacteria [162,163]. *Rhodococcus* sp. strain 36, *Bacillus* sp., strain 27, and *Bacillus gottheilii* have been documented to degrade polypropylene (PP) under regulated conditions [164,165]. Among invertebrates, *Achatina fulica* (giant African land snail) decomposed up to 30.7% of polystyrene within four weeks, while *Zophobas atratus* larvae showed similar degradation rates within a month. The microbiota of *Tenebrio molitor* and *Alphitobius diaperinus* larvae contains plastic-degrading bacterial and fungal species such as *Klebsiella*, *Pseudomonas*, *Serratia* and *Trichoderma*, which utilize MPs as a sole carbon source [164,166].

The above studies provide evidence for substantial potential of biological MP degradation through enzymes and associated microbiomes. However, the efficiency of degradation may differ considerably depending on polymer type and environmental factors, and further research on mineralization within natural ecosystems is still required.

6.3.3. Synthetically designed microbes for microplastic degradation

Engineered microorganisms have emerged as feasible bioremediation agents for the alleviation of microplastic (MP) pollutants, particularly in soil environments. Enhanced biofilm development and cell adhesion on microplastic substances significantly improve microbial degradation. Genetically engineered variants of *Stenotrophomonas pavanii* with improved biofilm development capabilities degraded polyethylene terephthalate (PET) microplastics faster compared to variants lacking biofilm development capabilities [167]. Similarly, increased expression of the curli operon in the *Escherichia coli* K-12 strain PHL644 enhanced biofilm development and cell adhesion under standard growth [168].

To target polyvinyl chloride (PVC), *Pseudomonas aeruginosa* was genetically modified by eliminating the *wspF* gene, thereby accelerating the production of sticky exopolymeric substances and enabling microplastics to adhere to its biofilm [169]. MP-degrading enzymes with enhanced efficacy, such as manganese-dependent peroxidase, PETase, laccase, and other enzymes involved in PET hydrolysis, have been engineered in *E. coli*, *Phanerochaete chrysosporium* and microalgae *Phaeodactylum tricornutum* and *Chlamydomonas reinhardtii* [170–174]. Whole cell biocatalysts competent at employing PET as a sole carbon source have successfully biodegraded microplastics using bacterial biocatalysts [175,176].

Pseudomonas, *Bacillus*, *Stenotrophomonas* and *Rhodococcus* spp. are dominant genera in MP biodegradation. Many studies report the involvement of enzymes such as hydrolases and alkane hydroxylases [177]. CRISPR/Cas9 genome editing has further improved the efficacy of these enzymes, thereby enhancing PET degradation rates under environmental conditions [108,178]. For instance, *Pseudomonas putida* modified with polyurethane-degrading esterase genes using Cas9 showed a 30% rise in monomer release in soil-like microcosms [179]. Similarly, a CRISPR/Cas9-engineered *Vibrio natriegens* strain secreting *Ideonella sakaiensis* PETase lost approximately half of its PET mass under saline conditions within one week [180]. Metabolically engineered microbial communities have also expanded plastic degradation targets to include PVC and polyurethane, in addition to PET [181].

Microcosm experiments show that PETase-expressing strains remain active in soil; although, challenges such as limited microplastic bioavailability, restricted enzyme diffusion and the risks of horizontal gene transfer necessitate rigorous ecological safety assessments [182]. Engineered microbes hold tremendous promise for tackling soil microplastics; however, environmental concerns and strict regulations on GMOs restrain their deployment in marine and terrestrial plastic pollution management (Fig. 4). Despite evidence from microcosm experiments showing that PETase-expressing strains function effectively in soils, issues related to MP bioavailability, enzyme movement, ecological interactions, and horizontal gene transfer complicate their industrial-scale application. These findings indicate that microbial engineering could be one of the most effective next-generation approaches for MP remediation; however, finding a balance between degradation efficiency and ecological safety remains a daunting task.

Adsorption and filtration techniques such as biochar and granular activated carbon are relatively simple and efficient approach for removing MPs and associated contaminants. Nanomaterial-based techniques ensure high efficacy of degradation and separation, despite uncertainties in the safety and applicability of nanomaterials on a larger scale. Bioremediation techniques are environmentally friendly but highly dependent on environmental factors and polymer types. Although microbial biodegradation of MPs offers promising degradation capability but has limitations due to biosafety and regulations, thus making its field application difficult. Hence, integration of physical, chemical, and biological treatment approaches may provide more promising results for MP management.

7. Preventive and system-level approach

A proactive and system-level approach is crucial for mitigating microplastic generation and accumulation in agroecosystems. Unlike remediation-based strategies that address already degraded ecosystems, preventive approaches underscore upstream interventions, mindful consumerism, circular economy principles, efficient waste management, and robust environmental mandates. Since the primary drivers and transport routes of microplastics are distinct between rural and urban regions, location-specific management approaches are required for long-term remediation. Effective remediation of microplastic debris is fundamentally anchored in individual accountability and sustainable consumption practices. Government intervention and policy support play a crucial role in microplastic pollution abatement. Policymakers must guarantee that biodegradable and recyclable substitutes remain accessible to the public, while imposing stringent measures on the production, application, and discarding of synthetic polymers. Policy frameworks such as Extended Producer Responsibility (EPR) ensure sustainable packaging, reusable products, and efficient collection and recycling of post-consumer plastic waste, thereby reinforcing circular economy-based plastic management [183]. Integration of EPR with single-use plastic bags and eco-friendly packaging's regulations further optimizes prolonged waste management strategies.

Circular economy approaches encompassing mechanical and chemical recycling, upcycling, and valorization technologies are widely acknowledged as sustainable strategies for curbing plastic and microplastic debris in the environment. Mechanical recycling lessens reliance on virgin plastics by converting waste into reusable products, although repeated recycling may lead to polymer degradation. Conversely, chemical recycling can recover virgin-grade monomers and retain polymer quality over repeated repolymerization runs. Advanced technologies such as nanocomposite fabrication, additive manufacturing, catalytic transformation, and industrial biotechnology enable the valorization of discarded polymers into value-added materials [184,185]. Identification of plastic polymers through Resin Identification Codes (RICs), such as polypropylene (PP-5) and low-density polyethylene (LDPE-4), can significantly optimize waste segregation, recycling efficiency, and facilitate the precise handling of plastic refuse.

Standardized monitoring, environmental surveillance, and data-sharing systems are also essential for system-level microplastic management. The Global Plastic Laws Database serves as a foundational

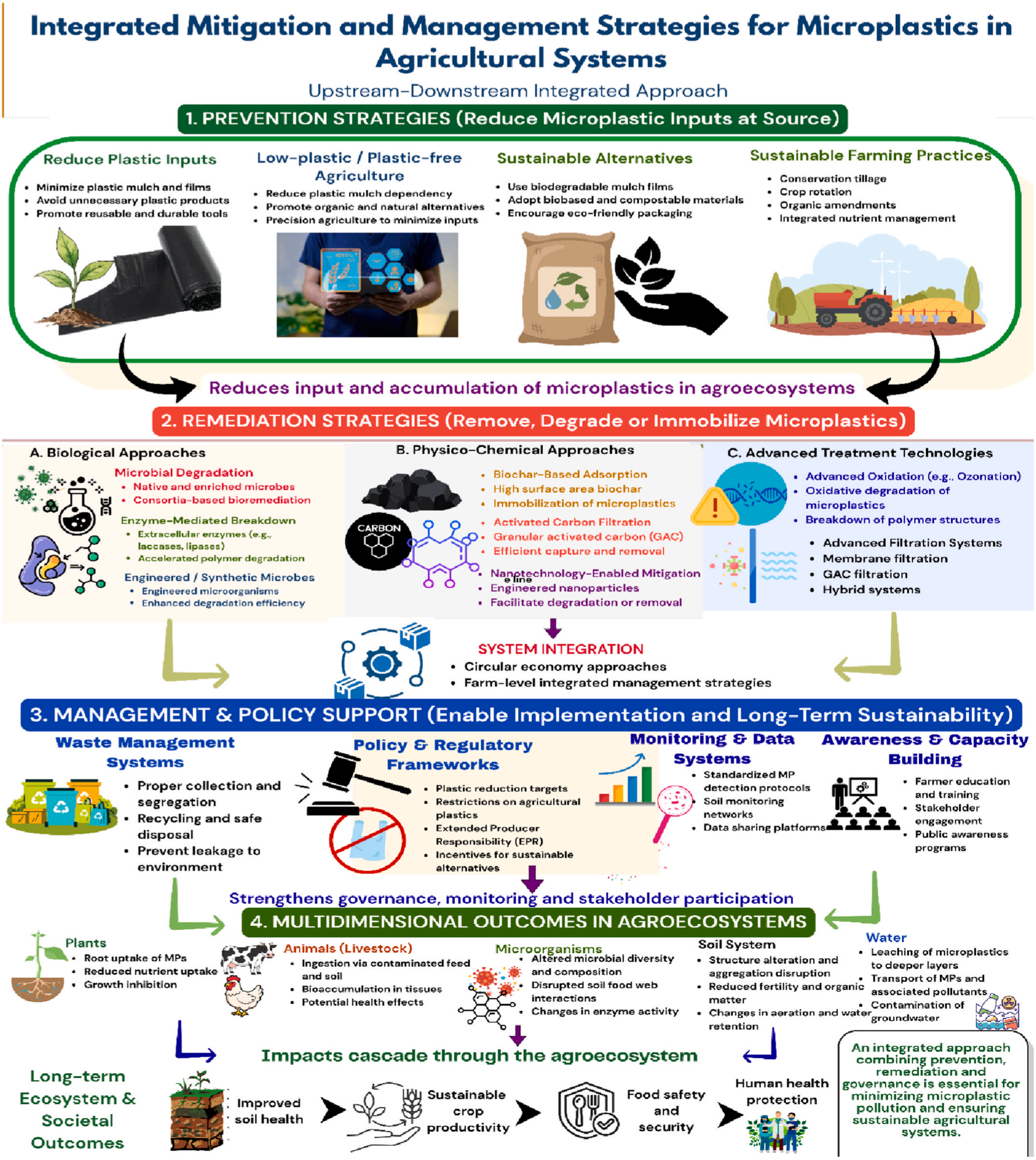

Fig. 4. The illustration presents a holistic source-to-sink continuum for intercepting, regulating, and mitigating microplastic (MP) pollution in agricultural systems. It delineates how preventive strategies, restorative innovations, legislative mandates, and sustainable stewardship synergistically operate to restrict MP retention and its cascading ecological consequences across agroecosystems.

repository for monitoring plastic-related legislation and policy developments worldwide [186]. Technologies such as remote sensing, AI-based monitoring, drone-assisted assessment, and in-situ techniques have enhanced the detection and quantification of plastic pollution throughout ecological communities [187–189]. Harmonized monitoring protocols and international standards such as ISO 15270:2008 are crucial for developing robust and comparable data on plastic production, recycling, and environmental leakage. Global initiatives together with UN-Habitat Waste Wise Cities Tool and Verra Plastic Waste Reduction Standard further strengthen evidence-based policymaking and collaborative mitigation strategies in accordance with Sustainable Development Goals (SDGs), particularly SDG 12.5 and SDG 14.1 [190].

At the regional level, preventive measures should be customized to address predominant contamination sources and transmission routes. In rural and agricultural regions, sustainable farming practices are inextricably dependent upon the accountable management of agricultural plastics. Substitution of conventional polymer-based mulch films with bio-based alternatives prepared from starch and agricultural residues, together with proper disposal of fertilizer and pesticide packaging materials, precise maintenance of irrigation infrastructure, regulated biosolid application, and plantation of erosion-resistant vegetation, can substantially curb microplastic contamination. Minimizing single-use plastics, fostering reusable and biodegradable alternatives, endorsing natural-fibre garments, and organizing community cleanup initiatives can further alleviate environmental plastic pollution. Community outreach programmes and extension activities are also instrumental in disseminating knowledge about the long-term ramifications of microplastics on public well-being and ecological integrity.

In urban regions, preventive frameworks should additionally emphasize on reducing plastic consumption and upgrading municipal sanitation systems. Prohibiting single-use plastics, encouraging reusable alternatives (e.g., steel or glass), deploying laundry and wastewater microfilters, and improving road management can mitigate the dispersion of microplastics into ecosystems. Avoidance of cosmetic products containing microbeads alongside the enforcement of recycling and upcycling protocols, are also important precautionary measures. Overall, the integration of sustainable consumption practices, circular economy paradigms, standardized monitoring systems, and stringent regulatory frameworks is essential for the phased mitigation of microplastic pollution and the safeguarding of terrestrial and agricultural ecosystems.

8. Research gaps and future perspective

Despite escalating research on microplastic contamination in terrestrial ecosystems, significant empirical blind spots remain unaddressed. While the majority of research is based on controlled laboratory experiments, there is a notable dearth of long-term field trials under authentic agro-ecological conditions. Variability in sampling, extraction, characterization, and quantification methods also impede cross-study comparisons, underscoring the need for systematized monitoring protocols. Current knowledge on the soil-plant continuum remains limited due to analytical constraints. Future research should emphasize the bioaccumulation and biomagnification of micro and nano plastics across trophic webs. Furthermore, interactions of microplastics with heavy metals, pesticides, antibiotics and soil microorganisms under various environmental conditions underscore the need for expanded empirical research.

Although biochar addition, microbial degradation, and nanotechnology-assisted remediation show significant potential, their transition from the laboratory to commercial application is often hindered by economic barriers and complex ecological risks. Likewise, the environmental and agronomic fate of biodegradable plastics and biocomposites needs to be assessed further. Therefore, future approaches to mitigation must focus on comprehensive frameworks involving sustainable agriculture practices, circular economy approaches, uniform monitoring frameworks, enhanced surveillance mechanisms, and policy interventions to sustainably manage microplastics within terrestrial and agricultural environments.

9. Conclusion

Microplastic pollution is one of the emerging concerns in terrestrial and agricultural ecosystems driven by its prolonged environment half-life and persistent accumulation in soils. Various agricultural inputs including synthetic fertilizers, irrigation systems, biosolids amendments, and wastewater irrigation are key vectors driving microplastic loading in terrestrial environments. These micro-debris undermine soil fertility, microbial communities, plant health, and groundwater quality, endangering food systems globally by acting as transport vectors of hazardous substances and pathogens. Various approaches namely biochar application, nanotechnology-based remediation, phytoremediation, and microbial biodegradation have revealed promising potential for eradicating microplastic contaminants. Nevertheless, their long-term efficiency and practical field applicability require further exploration. Effective management of microplastic pollution demands the synthesis of technological interventions, regulatory frameworks, robust waste management methodologies, circular economy approaches, and public awareness. Extended Producer Responsibility (EPR) frameworks, advanced recycling systems, biodegradable alternatives, and phasing out single-use plastics can help minimize ecological polymer leakage. Since sources and pathways of microplastics vary between rural and urban regions, region-specific preventive approaches are imperative for sustainable long-term mitigation. Overall, a collaborative framework integrating researchers, policymakers, industry leaders, farmers, and local communities are necessary for protecting soil health and ensuring sustainable agricultural ecosystems in the future.

CRediT authorship contribution statement

Munny Chinyo: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kalpana Bisht:** Formal analysis, Methodology, Project administration, Supervision, Visualization. **Meniari Taku:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Tony Manoj Nandipamu:** Conceptualization, Resources, Supervision, Visualization, Writing – review & editing. **Akash:** Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Shubham Singh:** Resources, Supervision, Validation, Visualization. **Riya Mehrotra:** Supervision, Validation, Writing – review & editing. **Sampurna Nand Singh:** Supervision, Validation, Visualization. **Hritik Srivastava:** Software, Supervision, Validation. **Abdul Mazeed:** Investigation, Resources, Supervision. **Priyanka Tewary:** Formal analysis, Investigation, Resources. **Sandeep Kumar:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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