Sources, Transport Mechanisms, and Ecological Risks of Microplastic Pollution in Arid Regions (Postprint)

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Abstract

Arid regions, as important source-sink areas for global microplastics (Microplastics, MPs), have unique climate conditions and human activity patterns that confer distinct characteristics to microplastic pollution. This paper systematically reviews the sources and pollution characteristics, migration patterns, and ecological risks of microplastics in arid regions in recent years. Regarding pollution characteristics, microplastic abundance in arid region soils exhibits significant spatial heterogeneity, with fibrous microplastics accounting for 64%~92%, and polyethylene (Polyethylene, PE), polypropylene (Polypropylene, PP), and nylon being the main components, among which agricultural film residues are the primary source. In terms of migration mechanisms, wind erosion and dust storm events dominate local-to-regional scale transport; fibrous microplastics, due to their high aspect ratio and low density, are more likely to achieve transboundary migration through atmospheric circulation; the coupling effect of electric fields and wind fields prolongs the atmospheric residence time of microplastics. Regarding ecological risks, microplastics produce multi-dimensional impacts on ecosystems by altering soil physicochemical properties (such as pore structure and water-holding capacity), interfering with microbial metabolism, and inducing oxidative stress in plants. Future research should focus on multi-scale model coupling, microplastic-contaminant combined effects, and the establishment of standardized monitoring systems.

Full Text

Preamble

Arid regions function as critical global source and sink areas for microplastics (MPs), where unique climatic conditions and human activity patterns cre-

ate distinctive pollution characteristics. This paper systematically reviews recent advances in understanding microplastic sources, pollution patterns, migration mechanisms, and ecological risks in arid environments. Regarding pollution characteristics, soil microplastic abundance exhibits significant spatial heterogeneity, with fibrous microplastics accounting for 64%-92% of the total. Polyethylene, polypropylene, and nylon constitute the main polymer types, primarily originating from agricultural film residues. In terms of migration mechanisms, wind erosion and sandstorm events dominate transport at local to regional scales. Fibrous microplastics, due to their high aspect ratio and low density, are particularly susceptible to cross-border migration via atmospheric circulation, with coupling effects between electric and wind fields extending their atmospheric residence time.

Ecologically, microplastics impact ecosystems multi-dimensionally by altering soil physicochemical properties (e.g., pore structure and water-holding capacity), interfering with microbial metabolism, and inducing oxidative stress in plants. Future research should prioritize multi-scale model integration, investigate the combined effects of microplastics and co-pollutants, and establish standardized monitoring systems.

Keywords: arid regions; microplastics; source; migration pattern; ecological risk

Microplastics (MPs) are plastic particles smaller than 5.0 mm and have become a global environmental concern [?]. Fibrous microplastics are more easily suspended and transported over long distances due to their high specific surface area. Wind erosion drives substantial microplastic migration fluxes, while arid and semi-arid regions—covering approximately 41% of global land area—exhibit increasing vulnerability to microplastic pollution in their fragile ecosystems. Arid regions develop unique microplastic pollution patterns due to distinctive climatic conditions (scarce precipitation, strong winds, high UV radiation) and human activity patterns (agricultural mulching, wastewater irrigation) [?]. Recent studies from northwestern China [?], Iran's Lut Desert [?], and the Tibetan Plateau [?] have revealed the ubiquity of microplastics in arid regions, yet significant knowledge gaps remain regarding their sources, migration mechanisms, and ecological risks.

Microplastic input pathways in arid regions show marked regional characteristics. Agricultural film residues represent the primary anthropogenic source [?], with secondary microplastics generated through fragmentation dispersing hundreds of kilometers via wind erosion [?]. Atmospheric transport constitutes another critical pathway, with 74%-99% of fibrous microplastics in Iranian deserts originating from urban and agricultural areas through wind transport [?]. Additionally, unique geomorphological features (e.g., yardang landforms, sand dunes) create significant spatial heterogeneity in microplastic distribution [?]. During sandstorms in desert areas, microplastic-laden dust easily adsorbs residual pesticides and bacteria [?], posing public health risks [?]. Research on microplastic sources, distribution, and potential ecological risks in arid regions is therefore of immense value for both scientific understanding and practical applications. Current studies show significant deficiencies in standardized monitoring methods, long-term effect assessments, and regional collaborative governance, necessitating an interdisciplinary research framework to address this emerging environmental challenge. This review systematically synthesizes recent findings on pollution characteristics, migration patterns, and ecological risks of microplastics in arid regions, while identifying research gaps and future directions.

1. Sources and Input Pathways of Microplastics in Arid Regions

Arid region microplastic sources include agricultural film fragmentation, tourism-related inputs, industrial production, and atmospheric deposition (sandstorms), with major polymer types comprising polyethylene (PE), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), and nylon (PA) [?]. Sources and migration pathways are complex and diverse, influenced by regional environmental characteristics and human activity patterns (Fig. [Figure 1: see original paper]). Agricultural film residues show high consistency with mulch materials [?], with residual quantities increasing with usage duration. Xinjiang' s farmland plastic residues far exceed national averages [?]. Mechanical tillage and UV radiation jointly cause film fragmentation, with soil microplastic abundance reaching 4,198-7,600 items $\cdot$ kg^{-1} in surface soils (0-20 cm) [?]. Extreme weather events (precipitation, sandstorms) and biological activity (e.g., animal ingestion) drive natural microplastic migration and distribution [?]. Greenhouse-covered plots, by suppressing wind erosion, exhibit slower microplastic degradation and greater accumulation. Irrigation also serves as an important source, with surface-water-irrigated farmland showing significantly higher microplastic abundance (326-2,406 items $\cdot$ kg^{-1}) than groundwater-irrigated (274-2,053 items $\cdot$ kg^{-1}) or treated wastewater-irrigated fields (114-800 items $\cdot$ kg^{-1}) [?]. Organic fertilizer application contributes substantially, with microplastic content reaching 39,629$±10,114*items* · *kg*^{-1}$ in manure, raising average abundance in Yan' an' s loess hilly region to 4,505$±435*items* · *kg*^{-1}$ [?]. Arid region soil microplastic sources also include domestic waste, plastic mulch, sewage sludge, floods, road runoff, and atmospheric deposition [?].

1.1 Agricultural Activity-Dominated Microplastic Input

Plastic mulching technology represents the core source of microplastic pollution in arid regions [?], having become a primary source of phthalate esters in air [?]. Farmland microplastic abundance increases with mulching duration, with non-mulched, 5-year, and 30-year rice fields showing 76.2$±18.4, 118.6±28.3, *and*159.6±23.5*items* · *kg*^{-1}$, respectively [?]. With continuous mulching (5-30 years), microplastic content increases substantially while particle size decreases with prolonged coverage. A nationwide survey of Chinese farmland soils revealed higher microplastic abundance in arid/semi-arid northern regions (e.g., Xinjiang) compared to temperate southwestern areas [?]. Gansu Province, China' s largest mulch user, experiences cold winters, hot summers, intense UV radiation, and strong autumn/winter winds [?], accelerating film degradation and soil accumulation. Due to continuous emissions and rapid film degradation, soil plastic content is projected to increase significantly over time [?].

Microplastics from film residues exhibit distinctive spatial distribution patterns. Vertically, surface soils (0-10 cm) show significantly higher abundance than deeper layers (20-30 cm), closely related to tillage disturbance and limited biological activity [?]. Salinity correlates with particle size distribution, with soil salt content positively correlated with 0.1-0.5 mm microplastic proportion but negatively correlated with <0.02 mm proportion, suggesting salinization controls degradation processes and elevates 0.1-0.5 mm particle proportion [?]. In the Qilian Mountains, different vegetation types show varying soil microplastic abundance: shrub areas (192.6$±23.5*items* · *kg*{-1}) > *forest*(159.6±18.7*items* · *kg*{-1}) > *grassland*(78.7±14.7*items* · *kg*^{-1}$) [?]. Urban functional zones with high human activity show elevated road dust and landfill-adjacent soil microplastic abundance [?]. Polymer composition also shows regional specificity: agricultural areas are dominated by PE and polyurethane (PU), consistent with mulch materials [?], while urban areas show PP dominance, reflecting packaging and construction material sources [?], and high-density polymers near industrial zones, likely from lubricant leakage [?].

1.2 Urban and Tourism-Related Microplastic Input

Urbanization intensifies multi-source microplastic inputs. Urban functional zones (parks, roads) show positive correlation between microplastic abundance and land-use intensity. Turkish urban soils contain predominantly blue fibers (92.9$±119.2*items*·*kg*{-1}), *mainlyfromtextilewearandplasticweathering*[?].*Industrialactivities*(*shipdismantling*, *portconstruct*
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items · kg⁻¹) and agricultural areas than industrial zones, with fibers dominating [?].

Wastewater treatment systems represent another important source. Qatari tertiary treatment achieves 87%-95% microplastic removal efficiency, yet effluent microplastics as heavy metal carriers still show detectable metal concentrations, indicating composite pollution risks [?]. Plastic waste primarily originates from floating litter, including common plastics like PE, PP, and PS [?].

Tourism impacts remote ecosystems significantly. Desert fringe areas with tourism show higher microplastic content (15.5$±11.7*items* · *kg*{-1})*thannon* − *touristareas*(1.5±0.7*items* · *kg*{-1})[?].*BadainJaranDesert*′*suninhabitedareasshowlowabundance*(
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higher microplastic abundance (850-1,556 items · kg⁻¹) than lake centers, primarily from protective gear abandonment, clothing fibers, and religious item

degradation [?]. Qilian Mountain eco-tourism areas show anomalously enriched microplastics, mainly PP, likely introduced through disposable tableware and other plastic products [?]. Traffic emissions contribute significantly, with tire wear particles notably increasing microplastic proportions near roads [?].

1.3 Atmospheric Transport Pathways for Microplastic Migration

Strong wind erosion in arid regions makes the atmosphere a critical channel for cross-media microplastic migration. Most microplastics on the Tibetan Plateau originate from Central Asian arid regions, with winter northwest winds transporting them over 1,000 km [?]. Notably, like dust aerosols, charged microplastics affect atmospheric aerosol composition, thereby influencing cloud formation and precipitation, which may alter aerosol size distribution, chemical composition, and radiative properties [?]. Rainfall processes play important roles in delivering atmospheric particulate matter to the surface [?]. Under identical air quality conditions, rainfall events increase particulate deposition flux, especially promoting deposition of fibrous particles and smaller grains [?]. Due to their lightweight nature, small particles remain airborne longer, resulting in higher abundance and easier migration during rainfall [?]. In arid regions with sparse vegetation, particulate matter easily accumulates on surfaces and transfers via surface runoff to estuaries and highway ditches after rainfall, potentially impacting local water supplies and ecosystems [?]. Future mitigation strategies may include filtering stormwater runoff before discharge or increasing vegetation coverage to reduce particulate migration [?].

Some desert regions experience extreme air masses and persistent snowfall. During snow events, atmospheric aerosol particles combine with water vapor to condense, forming rough, highly porous snow surfaces. Surface snowfall can aggregate aerosol particles through dry deposition [?]. High microplastic abundance occurs not only in urban snow but also in Arctic snow [?]. A study in Tabriz, Iran, found similar aerosol deposition numbers during rain and snow, though snow' s larger, less dense particles captured broader aerosol types and sizes [?]. As snow melts, aerosol particles are absorbed by soil, vegetation, or surface water through runoff [?]. Snowmelt plastic particle abundance is significantly higher than in nearby runoff, indicating snow accumulates plastics over time [?]. Aerosol particle numbers increase with decreasing size, potentially posing greater environmental risk than runoff due to acute release [?]. Therefore, treatment methods like sand filtration or pond sedimentation should be considered before snowmelt enters aquatic environments.

2. Spatiotemporal Characteristics of Microplastic Pollution in Arid Regions

Microplastic pollution distribution shows spatiotemporal variation in arid regions, with abundance differing by orders of magnitude across media at the same location. Even within the same medium, significant differences exist across depths or heights. Table summarizes microplastic abundance differences at selected arid region sites.

2.1 Spatial Heterogeneity in Soil Systems

Arid region microplastic distribution is significantly influenced by land-use type. In the Qilian Mountains, different vegetation types show varying soil microplastic abundance: shrub areas (50-325 items $\cdot$ kg^{-1}) > forest (50-1292 items $\cdot$ kg^{-1}) > grassland (~7.6\$×10^{3}\$ items $\cdot$ kg^{-1}) [?]. Notably, microplastic polymer composition shows regional specificity: the Tibetan Plateau atmosphere is dominated by PE and PU, consistent with mulch materials [?]; agricultural areas show PE dominance, matching film materials [?]; urban areas show PP dominance, reflecting packaging and construction sources [?]; and high-density polymers near industrial zones suggest lubricant leakage [?].

Vertical distribution is regulated by tillage practices. In continuously mulched cotton fields, microplastic abundance decreases from 4198-7600 items $\cdot$ kg^{-1} to 78.7\$±14.7*items* · *kg*^{-1}\$ with increasing soil depth, though long-term tillage alters profile distribution, resulting in no significant difference between 0-10 cm and 20-30 cm layers [?]. Microplastics show significant spatial differentiation across arid landforms: slope surfaces (1667-4333 items $\cdot$ kg^{-1}) show significantly higher abundance than tops (undetected) due to wind deposition; dynamic sand areas in dunes and mobile sands are prone to resuspension, while fixed dunes show surface enrichment due to vegetation interception; and seasonal lakes receive mountain microplastics via snowmelt runoff, though wind erosion contributes more [?]. Iran' s Lut Desert surface soil microplastic abundance reaches 1.1\$×10$^{\{3\}-7.8\times10}${3}\$ items $\cdot$ kg^{-1}, with 0.1-0.5 mm, 0.5-1.0 mm, and 1.0-5.0 mm particles comprising 28%, 45%, and 15% respectively [?].

2.2 Spatiotemporal Patterns of Atmospheric Microplastics in Arid Regions

Atmospheric microplastic types and abundance show significant seasonal variation. In Tehran, fragments dominate in summer (80.3-1075.6 items $\cdot$ m^{-2} $\cdot$ d^{-1}) while fibers dominate in autumn (0.74-1 items $\cdot$ m^{-2} $\cdot$ d^{-1}) [?]. Wuliangsu Lake in China shows distinct seasonal variation in atmospheric microplastic deposition flux, with spring > summer > autumn, and deposited microplastics are predominantly fibers (0-0.02 items $\cdot$ m^{-2} $\cdot$ d^{-1}) [?]. A study on atmospheric microplastic deposition in a northwestern semi-arid urban environment found total deposition flux fluctuating between 30-87 items $\cdot$ m^{-2} $\cdot$ d^{-1}, with urban periphery abundance 28 times higher than remote deserts [?]. Seasonal deposition patterns show summer [535.5 items $\cdot$ m^{-2} $\cdot$ d^{-1}] and autumn [197.5 items $\cdot$ m^{-2} $\cdot$ d^{-1}] as highest and lowest, respectively [?]. Particle size distribution reveals <100 m microplastics account for 45% of the total, while fibrous microplastics dominate [?]. Snow captures up to 92.9% fibers [?].

Intense weathering in arid regions drives significant microplastic miniaturization.

Atmospheric transport distances can exceed thousands of kilometers, with Tibetan Plateau microplastics primarily sourced from Central Asian arid regions over 1000 km away [?]. Sandstorms transport microplastics >0.5 mm, with 0.02-0.1 mm particles comprising 54% of the total [?]. Strong electric fields (>150 $\mathrm{kV \cdot m^{-1}}$) in arid regions can lift microplastics 80-250 m in diameter, reducing threshold friction velocity for wind-driven movement by 50% [?]. Urban atmospheric microplastic deposition fluxes are typically higher than non-urban areas, with PE as the main polymer type, fibers and fragments as dominant shapes, and 0.1-0.5 mm as the most common size range [?]. Soils near populated areas and intensively cultivated lands show the most severe contamination [?]. However, microplastics are also detected in remote areas like Chilean grasslands and the Tibetan Plateau, with atmospheric transport from developed areas being the primary migration pathway [?].

2.3 Microplastic Distribution in Arid Region Water Environments

Harsh conditions including high temperatures, rainfall, intense UV radiation, and sandstorms in arid regions exacerbate microplastic migration, distribution, degradation, and aging, leading to accumulation in valuable water resources and lakes. Water body microplastic abundance is strongly regulated by hydrological conditions. Wuliangsu Lake' s inlet shows high microplastic abundance (50-1292 $\mathrm{items \cdot L^{-1}}$), significantly higher than other open waters [?]. Burullus Lake' s open water average abundance (70.5$±36.5items · L{-1})ismarkedlylowerthanneardrainageditches(42.9±29.7items · L{-1})[?].Microplasticabundanceinaridregionwaterbodiesshowssignificantseasonalvariation : MansagarLakeinnorthwesternIndiashowslowerabundanceinpre−monsoonseason(50–325items· L{-1})thanpost − monsoon(850–1556items · L{-1})[?].BostenLake′saveragemicroplasticabundancedecreasesfrom28, L^{-1}$ in dry season to 67, 69-70 $\mathrm{items \cdot L^{-1}}$ in wet season [?].

Smaller particles are more easily wind-transported over long distances. Microplastic surface charge properties also affect atmospheric transport distance and residence time. Charged microplastics act as cloud condensation nuclei, adsorbing water molecules and prolonging atmospheric residence [?]. Wind-electric field coupling mechanisms result in transport distances exceeding traditional model predictions [?].

3. Migration Mechanisms of Microplastics in Arid Regions

3.1 Wind Erosion-Driven Horizontal Migration

Strong winds in arid regions are the primary driver of cross-regional microplastic transport. Previous research demonstrates that wind erosion is an important pathway for long-distance microplastic migration in terrestrial environments [?], particularly evident in arid and semi-arid regions where positive correlations exist between microplastic abundance in original soils and wind erosion deposits [?]. Wind tunnel experiments and field studies show higher microplastic abundance in wind erosion deposits than in original soils because lighter microplastics are more easily carried by wind than soil particles [?]. In sunflower and corn fields with extensive plastic mulching, microplastic abundance and fragmentation are significantly higher because tall crops anchor films near their stem-root systems, which then fragment due to agricultural practices (mechanical tillage, residue retention) and wind erosion [?].

Over time, accumulating microplastics damage soil structure, water-holding capacity, and microbial communities, eventually entering food chains [?]. Microplastics can penetrate plant cell membranes and walls or accumulate in root hairs, hindering nutrient and water uptake, reducing photosynthetic efficiency, and affecting common crops like wheat [?]. Microplastics can also be ingested by soil organisms, causing harmful physiological effects. Soil fauna such as earthworms accelerate microplastic migration [?], and biological transport leads to food chain transfer, threatening wildlife health and causing mortality [?].

3.2 Hydrological Migration of Microplastics

Surface runoff is a major collection point for microplastic particles and a key pathway for their transport into marine or inland environments via urban sewage, stormwater runoff, and atmospheric transport [?]. In desert regions, seasonal rainfall also transports microplastic particles from surfaces into rivers. For example, the Wei River (a Yellow River tributary in northwestern China) shows significantly lower microplastic content than the Yellow River estuary [?]. A study on microplastic distribution patterns, influencing factors, and potential ecological risks in surface water and sediments of the Yellow River' s arid regions identified particle size and flow velocity as primary factors affecting distribution and content [?]. In slower-flowing mid-lower reaches, polysulfonate pollution is more prevalent, and smaller particles are more likely to settle [?].

Although atmospheric deposition is an important source of microplastics in arid region water bodies, endogenous lake processes should also be considered, as pollutants accumulate during filling and evaporation cycles, resulting in high microplastic abundance [?]. Intermittent flooding is a crucial driver of microplastic redistribution in arid regions. Monitoring of the Santa Cruz River showed increased waterborne microplastic fragment abundance and decreased sediment fiber content post-flood, reflecting strong runoff' s scouring effect on bottom sediments [?]. This pulsed input creates zonal microplastic distribution in floodplains, with >1.0 mm particles mainly retained 50-100 m from channels [?].

Irrigation and precipitation drive microplastic migration to deep soil and groundwater. Drip irrigation or snowmelt transports small-sized microplastics downward, with fiber proportion decreasing from 64%-92% to 28%-45% as soil depth increases [?]. During rainy seasons, fibrous materials are the most abundant microplastic type [?]. Arid region-specific macropore structures facilitate rapid microplastic migration, though this process reduces soil porosity. Microplastics (0.1-5.0 mm) can reduce non-saline soil total porosity by 2%-7% and saline soil porosity by 2%-8% [?].

3.3 Biologically Mediated Migration and Transformation

Microplastics alter soil microbial communities and carbon metabolism, increasing greenhouse gas emissions. The environmental effects of microplastic pollution in arid regions are multi-dimensional, with potential ecological risks ultimately threatening human health through food chain transfer (Fig. [Figure 2: see original paper]). Microplastics accumulate in soil, can concentrate around plant roots and even enter plant tissues, affecting crop growth and yield, and potentially entering the human body through the food chain, posing health risks [?].

4. Environmental Effects and Ecological Risks of Microplastic Pollution in Arid Regions

4.1 Impacts of Microplastics on Arid Region Soil Ecosystems

Due to the threat microplastics pose to terrestrial ecosystems, soil research has increased substantially in recent years [?]. Surface soils (0–20 cm) from long-term plastic film-covered farmland in Xinjiang, Liaoning, Sichuan, and Shandong showed that prolonged mulching significantly increased microplastic accumulation in surface layers (especially 0–10 cm) and altered soil properties. Surface soil (0–10 cm) organic carbon, total nitrogen, and available phosphorus increased by $<0.05\%$, 15%, and 46%, respectively [?]. Although traditional mulch films improve water use efficiency and reduce irrigation demand [?], long-term use in artificially watered or water-deficient arid sandy topsoil may cause soil compositional and ecological changes, eventually becoming drier and even hydrophobic [?]. Short-term exposure (3 months) can reduce silt-clay water-holding capacity [?]. Long-term mulching decreases soil aggregate stability and accelerates nitrogen loss [?]. Microplastics also accelerate soil organic carbon (SOC) mineralization, with PE-amended soils showing the highest CO_2 emissions, followed by PP and control soils [?].

Arid region soil microplastics severely impact soil microbial population distribution and numbers by reducing water retention and nutrient content [?]. Long-term plastic mulching affects soil bacterial communities, with films serving as microbial carbon sources, increasing plastic-degrading bacteria. Many films remain unrecovered, accelerating soil microplastic accumulation, while degradation-released additives worsen pollution [?]. Compared to forest and farmland soils, microplastics cause greater disturbance to bacterial communities in sandy soils, affecting carbon and nitrogen cycling [?]. Critically, harmful substances produced during microplastic aging or degradation may cause population reductions or extinctions. A survey of arid farmland in northern Shaanxi found plastic film residues released phthalates, increasing soil phthalate content annually, significantly altering bacterial community structure and interfering with metabolic functions [?].

Desertification-associated extreme climatic conditions support limited plant species and numbers, making vegetation highly sensitive to environmental changes. Consequently, microplastic pollution in desert ecosystems often exerts greater negative impacts on local vegetation [?]. Microplastics reduce soil water absorption and permeability by altering physical properties, subjecting plants to more severe drought stress and threatening their growth, development, and survival [?]. Microplastics reduce corn biomass by 50% and Rubisco enzyme activity by >30% at 50.0 $\mathrm{mg} \cdot \mathrm{L}^{-1}$ concentration [?].

4.2 Effects of Microplastics on Aquatic Organisms and Ecological Risks

Arid region lakes are important microplastic sinks, with Wuliangsu Lake showing atmospheric deposition up to 2266\$±271$items\cdot m^{\{-2\}\cdot d}$\{-1\}\$ and waterborne abundance reaching 70.5\$±36.5$items \cdot L$^\{-1\}\$, predominantly small-sized microplastics (<2.0 mm) comprising 54%-94% of the total [?]. Ingested microplastics likely cause adverse effects including mechanical damage, reduced growth, and physiological stress (immune responses, metabolic abnormalities, behavioral changes, and altered energy budgets) [?]. For example, high-dose PE microplastics cause reproductive dysfunction in some aquatic organisms [?].

Besides the plastics themselves, adsorbed environmental toxins (e.g., plastic additives, phthalates, bisphenol A, reactive plastic monomers, and other organic pollutants) may bioaccumulate through food chains, posing significant threats to higher trophic level organisms, including humans [?]. A recent study on human-derived cells confirmed that polystyrene microplastics increase reactive oxygen species production, causing acute inflammation and cell death in immune cells [?].

4.3 Microplastic Surface Pollutant Adsorption Exacerbates Ecological Risks

Microplastic surfaces adsorb pollutants, creating composite contamination that intensifies ecological risks. Arid region-specific salinity conditions promote co-precipitation of microplastics and pollutants, elevating composite ecological risks [?]. Microplastic-salt combined stress increases corn leaf malondialdehyde content [?]. Dust containing microplastic particles poses greater environmental risk due to large specific surface area and toxic substance adsorption capacity [?]. A simulation study suggests Central Asian public health issues may be attributed to Alakum Desert sand carrying plastic particles, as dust can easily transport pathogens or other pollutants across the region [?].

4.3.1 Microplastic-Phthalate Composite Pollution Characteristics As bulk plastics decompose and microplastics form, plastic additives such as phthalates (PAEs) are released into the environment [?]. Arid region agricultural film-derived microplastics show strong phthalate affinity, with surface hydrophobicity and crack structures significantly enhancing adsorption capacity. For example, plastic mulch films (PE) contain extremely high phthalate levels (up to 65.3 $\mathrm{mg \cdot kg^{-1}}$), easily creating microplastic-phthalate composite pollution [?]. As hydrophobic semi-volatile organic compounds, phthalates are not chemically bound to plastics but associate through weak interactions (hydrogen bonds, van der Waals forces), maintaining relatively independent chemical properties [?]. Consequently, phthalate release rates increase substantially when films age or decompose [?]. As typical environmental hormones, phthalates are potentially carcinogenic, teratogenic, and mutagenic, bioaccumulating through food webs and interfering with endocrine functions, posing threats to life and health [?].

4.3.2 Microplastic-Persistent Organic Pollutant Composite Pollution Characteristics Agricultural mulch films are easily contaminated by pesticides, making them difficult to treat and recycle. PE films can absorb pesticides and other organic/inorganic substances through amorphous regions, facilitating transfer of pesticides, antibiotics, and other pollutants to soil and plants [?]. Under 5 $\ \mathrm{g \cdot L^{-1}}$ and 200 $\ \mathrm{g \cdot L^{-1}}$ PAH concentration levels, mulch microplastic (PE) adsorption amounts for naphthalene are 11 and 111 $\ \mathrm{g \cdot g^{-1}}$, respectively, influenced by octanol-water partition coefficient (Kow) and ionic strength [?]. Compared to pure PE microspheres, extracted microplastic adsorption rates for PAHs are 45% higher [?]. Microplastic aging and adsorption of PAHs are important factors in oxidative stress for aquatic organisms [?].

4.3.3 Microplastic-Heavy Metal Composite Pollution Characteristics Microplastics as pollutant carriers can also enrich heavy metals. A study of microplastics from Ebinur Lake Basin soils in a typical arid oasis found 8 heavy metals significantly positively correlated with soil SOC content ($P<0.01$), indicating heavy metals on microplastic surfaces mainly originate from soil fertilization and are influenced by SOC and total salt content [?]. Iranian urban soil microplastics carry Cd and Pb concentrations reaching 15 and 46 times soil background values, respectively [?]. Polystyrene microplastics show high affinity for Cu and Zn, with absorption of [173 $\ \mathrm{g\ Zn \cdot (g\ C)^{-1}}$] and [1192 $\ \mathrm{g\ Cu \cdot (g\ C)^{-1}}$] [?]. In urban soils, traffic-intensive areas show synthetic rubber particle (containing Zn) content 30× higher than agricultural areas [?]. Aging microplastics have more oxygen-containing groups providing binding sites, increasing heavy metal adsorption, with aged PE adsorbing more Cu(II) than pristine PE [?].

5. Future Priority Research Areas

As global climate change intensifies and human activities increase, arid region microplastic pollution has transcended traditional environmental boundaries, exhibiting cross-media, cross-scale, and cross-regional complexity. Its environmental behavior and ecological effects urgently require systematic analysis. Future research must overcome current methodological limitations and construct innovative interdisciplinary paradigms, focusing on the following core areas: establishing arid region-specific microplastic life-cycle monitoring systems, revealing multi-interface coupling migration mechanisms, quantifying long-term ecological risk thresholds, and developing nature-based social collaborative treatment technologies. These priority breakthroughs will provide scientific support for maintaining arid region ecological security and sustainable development.

5.1 Multi-Scale Monitoring Methods and Standardized System Construction

The primary challenge facing current arid region microplastic research is regional adaptability and data comparability of monitoring methods. Traditional sampling and analysis methods have significant limitations when dealing with complex arid region matrices (e.g., high-salt soils, dusty atmospheres), particularly insufficient identification precision for nanoscale plastics, degradation intermediates, and heterogeneous composites. Future development should focus on multi-modal detection technologies integrating spectroscopic fingerprint recognition, isotopic tracing, and artificial intelligence algorithms to establish in-situ characterization systems covering macro-to-nano scales. For arid region-specific wind-blown sand migration characteristics, continuous aerosol collection and real-time analysis devices should be developed, combined with satellite remote sensing and ground sensor networks to construct an "air-space-ground" integrated monitoring system. Additionally, natural archives like historical sediments and ice cores should be studied for microplastic source tracing, reconstructing century-scale pollution evolution to provide baseline data for future scenario prediction.

5.2 Multi-Media Interface Processes and System Coupling Mechanisms

The unique environmental behavior of microplastics in arid regions stems from multi-interface coupling migration characteristics, which exhibit nonlinear amplification effects under climate change. Future research must break through traditional single-medium study paradigms, focusing on revealing four coupling mechanisms: atmospheric-soil interface deposition dynamic equilibrium, soil-plant system rhizosphere microdomain transport, surface water-groundwater system preferential flow-driven mechanisms, and biotic-abiotic interface surface modification effects. Multi-process coupled mathematical models should be established, integrating parameters for physical fragmentation, photochemical aging, and biofilm formation to quantify cross-media fluxes under different climate scenarios. Particular attention should be paid to the regulatory effects of arid region-specific processes (wet-dry alternation, freeze-thaw cycles) on microplastic surface properties and migration capacity, clarifying interaction mechanisms between environmental factors (salt gradients, electric field intensity) and microplastic colloidal behavior.

5.3 Ecological Risk Thresholds and Adaptive Management Pathways

Ecological risk research on arid region microplastics must shift from hazard identification to quantitative management. Current research severely lacks understanding of long-term low-dose exposure effects, combined pollution synergistic effects, and ecological thresholds. Future work should establish multi-trophic-level exposure experimental systems, focusing on combined effects of microplastics and typical arid region stressors (high temperature, salinity, dust storms), analyzing molecular mechanisms affecting soil microbial functional gene expression, plant water-use strategies, and animal immune responses. Traditional toxicological assessment frameworks should be transcended to develop ecosystem service function-based risk assessment models, quantifying microplastic disturbance intensity on critical ecological processes like carbon-nitrogen cycling and water regulation. At the treatment technology level, research should prioritize biomimetic degradation materials, intelligent recycling equipment, and ecological interception systems, developing full-chain technical systems from "source reduction to end remediation," and establishing blockchain-based agricultural film recycling incentive mechanisms and cross-border ecological compensation mechanisms to form arid region-specific microplastic governance solutions.

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Note: Figure translations are in progress. See original paper for figures.