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The Silent Snowfall: Formation, Advanced High-Resolution Mass Spectrometric Analysis, and Human Health Impacts of Microplastics in Central Asia

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Abstract: Microplastics and nanoplastics now turn up in nearly every environmental compartment that has been sampled, yet most research has focused on marine and coastal systems. Mountainous, continental regions such as Central Asia remain poorly studied. This review follows microplastics through the Central Asian setting, from their formation to their fate in the human body. It is based on a structured search and thematic synthesis of 70 peer-reviewed sources published between 2008 and 2026. Primary particles come mainly from synthetic textiles and tire wear in fast-growing cities, while secondary particles form when mismanaged plastic waste is broken down by intense high-altitude ultraviolet radiation and repeated freeze-thaw cycles. Air currents carry these particles over long distances and deposit them on the snow and glaciers of the Tien Shan, the Pamir and the neighboring Tibetan Plateau. There they lower surface albedo and can speed up melting of the “Asian Water Tower,” releasing stored particles and their adsorbed chemicals into the Amu Darya and Syr Darya basins. Spectroscopic methods identify the polymer itself, but the mobile chemical fraction, which includes plasticizers, bisphenols and degradation oligomers, is best characterized by liquid chromatography coupled to high-resolution mass spectrometry (LC-HRMS). We describe contamination-control practice, notably the use of a delay column, and the use of the Schymanski confidence scale in non-target screening. We then summarize evidence that microplastics reach human blood, lung and placenta, that nanoplastics can cross the blood-brain barrier in experimental models, and that plastic particles have been found in carotid plaques of patients who went on to have worse cardiovascular outcomes. Proposed mechanisms include “Trojan Horse” transport of sorbed pollutants and blood-brain barrier disruption through the TLR2/MMP9 axis. We close with priorities for harmonized analytical standards, transboundary monitoring, and long-term toxicological and epidemiological work.

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Keywords: microplastics; nanoplastics; Central Asia; cryosphere; albedo; LC-HRMS; non-target screening; Schymanski confidence scale; Trojan Horse effect; human health

1. Introduction

Microplastics, usually defined as synthetic polymer particles smaller than 5 mm in their longest dimension, and nanoplastics, which are smaller than 1 μm , have been detected in every ecological compartment that has been measured [1]. The topic began as a marine pollution problem. It now covers land, air and ice as well. How these particles behave, how long they last, how they degrade and what they eventually do to living tissue all depend on regional climate, topography and human activity. Central Asia is an especially exposed setting for the accumulation and release of microplastics [2].

The region combines continental steppe, arid desert and high mountain ranges, above all the Tien Shan and the Pamir, and it depends heavily on its high-altitude cryosphere. Glaciers and seasonal snowpack are the main freshwater stores of the endorheic Aral Sea Basin, and they support agriculture, industry and drinking water for millions of people [3], [4]. That system is already under strain. Regional temperatures are rising at nearly twice the global average, glaciers are retreating quickly and historical runoff patterns are shifting [3], [5]. Airborne microplastics add two more problems to this fragile setting: they act as a new climate forcing agent, and they carry chemical contamination into the water system.

Central Asia lies close to major industrial and population centers in South Asia and East China and has fast-growing cities of its own, so it receives both local and transboundary airborne pollutants [2]. Counting particles, however, tells only part of the story. Plastics are chemically active materials. They contain unreacted monomers, intentionally added additives (plasticizers, flame retardants, ultraviolet stabilizers) and pollutants picked up from the environment [1], [6]. The aim of this review is to connect the physical formation and transport of microplastics in Central Asia with their chemical characterization by liquid chromatography-mass spectrometry (LC-MS), and then with the health risks that follow when they accumulate in the human body. Figure 1 gives an overview of the pathway we follow.

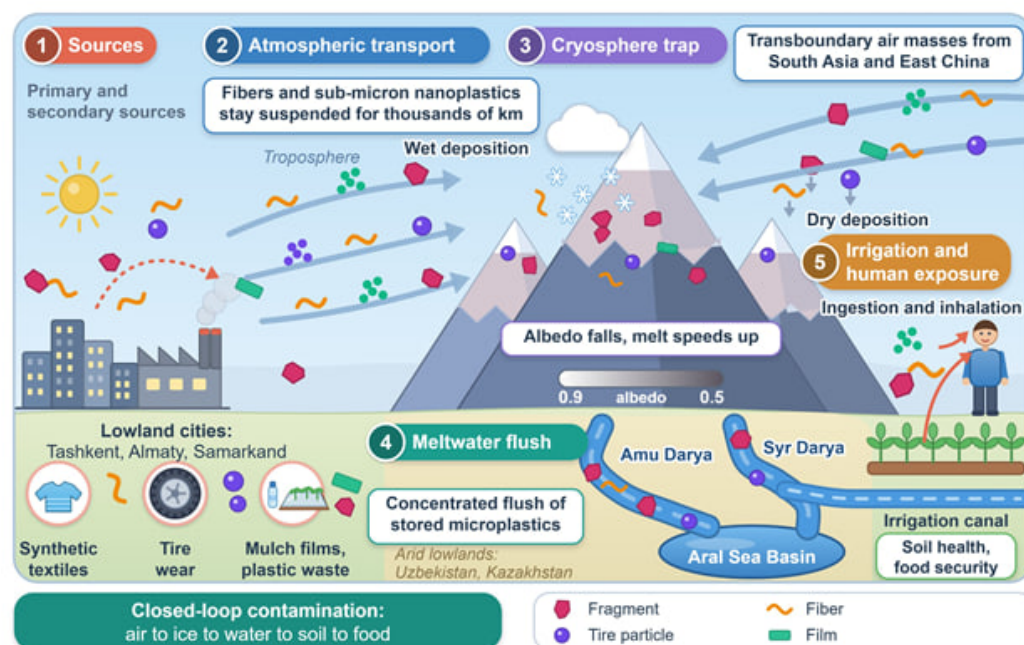


Figure 1. Source-to-sink pathway of microplastics in Central Asia. Urban, industrial and agricultural sources release fibers, tire particles and plastic fragments. Winds, including transboundary air masses from South Asia and East China, carry the particles to the Tien Shan and Pamir, where snowfall and dry deposition trap them in snow and glaciers. Lower albedo speeds up melt, and meltwater flushes the stored particles into the Amu Darya and Syr Darya. Irrigation returns them to farmland, and people are exposed by ingestion and inhalation.

2. Materials and Methods

2.1 Review Design and Literature Search

This study was designed as a structured narrative review that follows microplastics along a source-to-sink pathway, from their formation to their effects on human health (Figure 1). Peer-reviewed literature was identified in the Scopus, Web of Science Core Collection, PubMed and Google Scholar databases using combinations of the following keywords: "microplastics", "nanoplastics", "Central Asia", "Tien Shan", "Pamir", "Tibetan Plateau", "snow", "glacier", "albedo", "Amu Darya", "Syr Darya", "LC-MS", "LC-HRMS", "non-target screening", "plastic additives", "Trojan horse", "blood", "placenta" and "cardiovascular". The reference lists of key reviews were also screened to find additional relevant studies.

2.2 Eligibility Criteria

Peer-reviewed original articles and reviews published in English between 2008 and 2026 were included if they addressed at least one of four domains: (i) sources and formation of microplastics; (ii) their atmospheric, cryospheric or hydrological transport in Central Asia or in comparable high-mountain continental regions (the Tibetan Plateau and Western Siberia); (iii) analytical methods for microplastics and their chemical additives, with emphasis on LC-MS and LC-HRMS; and (iv) human exposure, bioaccumulation and toxicity. Duplicate records and sources without a verifiable bibliographic record were excluded. After screening, 70 sources were retained for the synthesis.

2.3 Data Extraction and Synthesis

For each study, the region, sampled matrix, particle morphology, polymer types, analytical technique and main quantitative findings were recorded. The evidence was then synthesized thematically along the source-to-sink pathway. Analytical studies were assessed in terms of contamination control and identification confidence, using the Schymanski scale for non-target screening results. For health studies, observational evidence in humans was distinguished from in vitro and animal experiments, so that associations are not presented as proven causal effects.

3. Results and Discussion

3.1 Characteristics of the Reviewed Literature

The final dataset comprised 70 sources. Of these, 40 (57%) were published in 2024–2026, 22 (31%) in 2020–2023 and 8 (11%) before 2020, which shows that the field is developing rapidly. Their distribution by thematic domain is given in Table 1.

Table 1. Distribution of the reviewed sources by thematic domain (by section of first citation).

Thematic domain	Section	Number of sources	Share, %
Background and regional context	1	6	8.6
Formation and sources	3.2	12	17.1
Transport and environmental fate	3.3	11	15.7
Analytical identification (LC-MS/HRMS)	3.4	14	20.0
Human health impacts	3.5	26	37.1
Mitigation and policy	3.6	1	1.4

Thematic domain	Section	Number of sources	Share, %
Total		70	100.0

Only four of the reviewed sources report microplastic data from Central Asia itself: a critical review of wastewater systems in Kazakhstan and Central Asia [7], a pilot study of snow in the Zhetysu region of Kazakhstan [8], and two studies of river basins in Uzbekistan [9], [10]. Evidence on atmospheric transport and cryospheric processes therefore comes mainly from analogous high-mountain and continental regions, such as the Tibetan Plateau [2], [11] and Western Siberia [12]. This scarcity of regional data is itself a key result of the review, and it defines the research priorities discussed in Section 3.6.

3.2 Formation and Sources of Microplastics in Central Asia

Microplastics in the Central Asian environment come from rapid urbanization, changing agricultural practice and a climate whose extremes speed up polymer breakdown. Sources fall into primary and secondary groups, and each has its own physical and chemical signature (Figure 2).

3.2.1 Primary Microplastics: Urban and Industrial Sources

Primary microplastics are either manufactured at microscopic size for a specific use or released directly as tiny fragments when consumer goods wear down. In the growing urban corridors of Central Asia, including Tashkent, Almaty and Samarkand, the main emission routes are the shedding of synthetic textile fibers and tire wear particles (TWPs) [10].

Synthetic clothing (polyester, nylon, acrylic) sheds microfibers every time it is washed [13]. A weak point in the region's infrastructure is the limited capacity of its wastewater treatment plants (WWTPs). Removing microplastics almost completely takes advanced tertiary or polishing steps, such as membrane bioreactors or ultrafiltration, and these are often missing [7], [14]. Conventional secondary treatment keeps a large share of microplastics in the sewage sludge but still releases substantial numbers of microfibers into receiving rivers [7]. The sludge, loaded with captured particles, is often spread on farmland, where wind dispersion and surface runoff turn it into a secondary emission source [7].

At the same time, the growth of road traffic has made TWPs a major terrestrial and atmospheric contaminant. They form when tires erode against the road surface, and they are heavily modified elastomer particles rather than pure rubber. They are dense chemical mixtures containing vulcanizing agents, heavy metals and antioxidant degradation products. Urban runoff carries them into local watersheds, and some are lofted into the air as particulate matter [15], [16].

3.2.2 Secondary Microplastics: High-Altitude Degradation

Most of the microplastic burden in Central Asia appears to be secondary, formed as larger plastic waste fragments under intense environmental stress [7]. Waste management has not kept pace with the rapid growth in single-use packaging and agricultural plastics such as polyethylene mulching films, and a lot of this material leaks into the environment [17].

Geography speeds up the mechanical and chemical breakdown. In the high-altitude zones of the Tien Shan, the Pamir and the Tibetan Plateau, ultraviolet (UV) radiation is much more intense [18]. UV exposure drives photo-oxidation, mainly through free radicals that cut the carbon-carbon backbone of polyolefins [19]. The plastic becomes brittle. Combined with large day-night temperature swings and frequent freeze-thaw cycles in the continental climate, embrittled macroplastics break down quickly into micro- and nanoplastics [19]. The result is a sharp rise in local particle counts and a much larger reactive surface area from which toxic additives can leach [19].

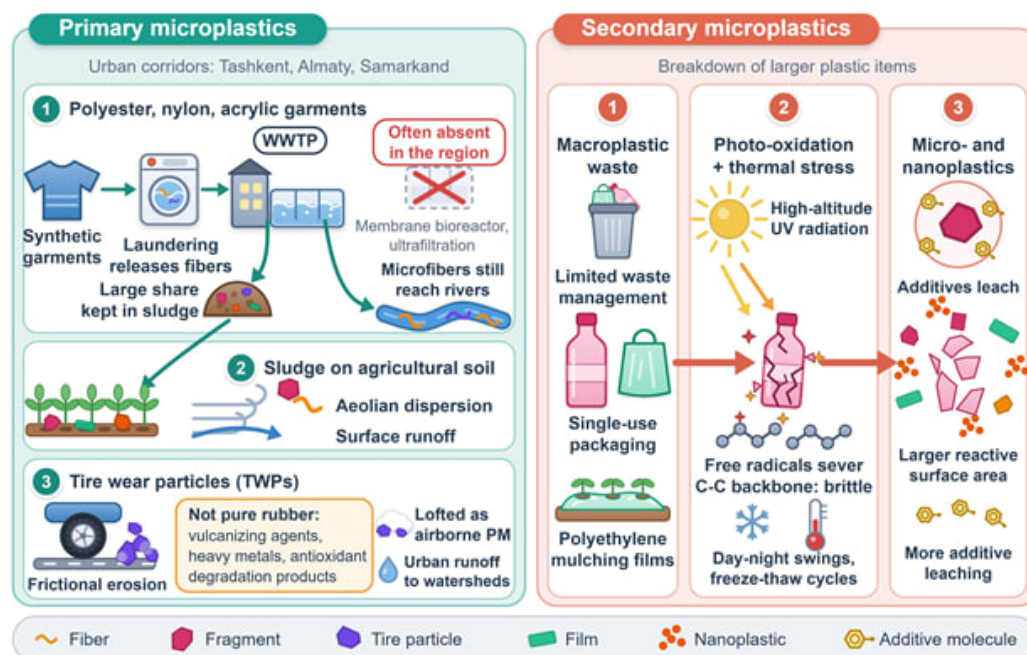


Figure 2. Formation pathways of microplastics in Central Asia. Primary particles arise from laundering of synthetic textiles, with partial retention in wastewater treatment plants and sludge reuse on farmland, and from tire wear. Secondary particles form when macroplastic waste is embrittled by intense UV radiation and fragmented by temperature swings and freeze-thaw cycles, which also exposes more surface for additive leaching.

3.2.3 Polymer Profiles in Regional Ecosystems

Recent field studies in Central Asian freshwater and cryosphere systems give a first quantitative baseline for regional polymer profiles. A pilot study of snow cover in the Zhetysu region of Kazakhstan found substantial microplastic accumulation, and Raman spectroscopy showed that polyethylene (PE), polypropylene (PP) and polystyrene (PS) dominated [8]. This mix closely resembles typical municipal packaging waste and shows how atmospheric transport redistributes urban pollution to remote areas.

In Uzbekistan, assessments of the Kara Darya, Chirchiq and Zerafshan rivers, which feed the Syr Darya and Amu Darya basins, showed distinct morphological and chemical profiles. Microfibers made up most of the particles in surface water. In the Chirchiq River they accounted for more than 95% of the microplastic load, mostly in the 0.30 to 1.00 mm size range [9]. Studies in the Tashkent and Jizzakh basins pointed the same way, with microfibers (45%) and fragments (35%) as the dominant shapes and polyethylene terephthalate (PET) and PP as the dominant polymers [10].

Researchers rate the ecological risk of these polymers with indices such as the Pollution Load Index (PLI) and the Polymer Hazard Index (PHI). Work on stable snow cover in a comparable continental climate, Western Siberia, used the PHI to show that even when the overall pollution load looks low, polyacrylonitrile (PAN) and polyurethane (PU), whose monomers are carcinogenic and mutagenic, can push the local hazard into the “extreme danger” category. This argues for careful monitoring of neighboring Central Asian snowpacks [12]. Table 2 summarizes the profiles reported so far for snow and rivers in the region.

Table 2. Morphology, dominant polymers and inferred sources of microplastics in Central Asian snow and river systems.

Central Hydrological Feature	Asian	Predominant Morphology	Dominant Polymer Types	Inferred Emission Source	Primary
Zhetysu Region (Kazakhstan)	Snow	Fragments, Fibers	PE, PP, PS	Atmospheric fallout, urban waste [8]	
Chirchiq (Uzbekistan)	River	Fibers (>95%)	PET, PP, PA	Domestic wastewater, synthetic textiles [9]	
Kara Darya (Uzbekistan)	River	Fibers, Fragments	PET, PE, PP	Mixed urban/agricultural runoff [9]	
Lake Tuzkon (Uzbekistan)	Basin	Fragments, Films	PE, PP, TPEE	Mismanaged waste, agricultural films [10]	

3.3 Transport and Environmental Fate

Microplastics are light and persistent, so they travel easily over long distances. In Central Asia their fate is governed by three linked processes: atmospheric circulation, deposition in the cryosphere, and hydrological flushing.

3.3.1 Atmospheric Transport Dynamics

Atmospheric transport is now recognized as a main route for the global spread of micro- and nanoplastics, which lets particles cross terrestrial barriers and reach remote, apparently pristine areas [2], [20]. In Central Asia, broad lowland steppes rise abruptly into high mountain ranges, which creates complex airflow corridors. Particles emitted by regional urban areas, together with those brought in by transboundary air masses from South Asia and East China, are lifted by turbulent flows and regional monsoon dynamics [2].

Fibers and sub-micron nanoplastics are light enough to stay in the troposphere for long periods and can travel thousands of kilometers [21]. Studies of microplastic deposition in surface snow of the Tibetan Plateau, the “Third Pole” next to the Pamir and Tien Shan, indicate that atmospheric circulation is the main way these pollutants reach glaciers far from direct human activity [2]. Their distribution also changes with elevation. Lower-altitude areas near dense urban sources show higher absolute concentrations, whereas remote high-altitude zones receive finer, more weathered particles, a sign of extensive long-range transport [11].

3.3.2 The Cryosphere Trap and Albedo Reduction

When suspended microplastics reach the Tien Shan and Pamir, wet deposition (snowfall and precipitation) and dry deposition remove them from the air and lock them into the cryosphere. Seasonal snowpacks and glaciers act as large sinks and store decades of atmospheric fallout [8], [22]. This build-up, however, sets off a local thermodynamic feedback that affects regional climate stability (Figure 3).

Surface albedo, the share of sunlight a surface reflects, strongly controls how much energy is available to melt snow and glaciers [23]. Clean snow is highly reflective and absorbs little heat. Climate models have long included the albedo-lowering effects of black carbon (BC) and mineral dust, but recent physics-based work suggests that microplastics also play a significant role in this energy balance, one that has so far gone unquantified [21]. Both colored and translucent microplastics absorb shortwave solar radiation. As initially transparent polymers weather through photo-oxidation, their

surfaces become scratched, pitted and opaque, which greatly increases their ability to absorb heat [19].

Measurements on high-altitude glaciers show that enrichment of particulate matter on the snow surface can lower local albedo from 0.9 to 0.5, which changes the reflectance spectrum substantially [24]. Because microplastics can persist in snowpack for hundreds of years, their cumulative deposition acts as a lasting climate forcing. This could speed up the melting of the Tien Shan and Pamir glaciers beyond what rising greenhouse gas concentrations alone would predict, and it complicates traditional black carbon forcing models [21].

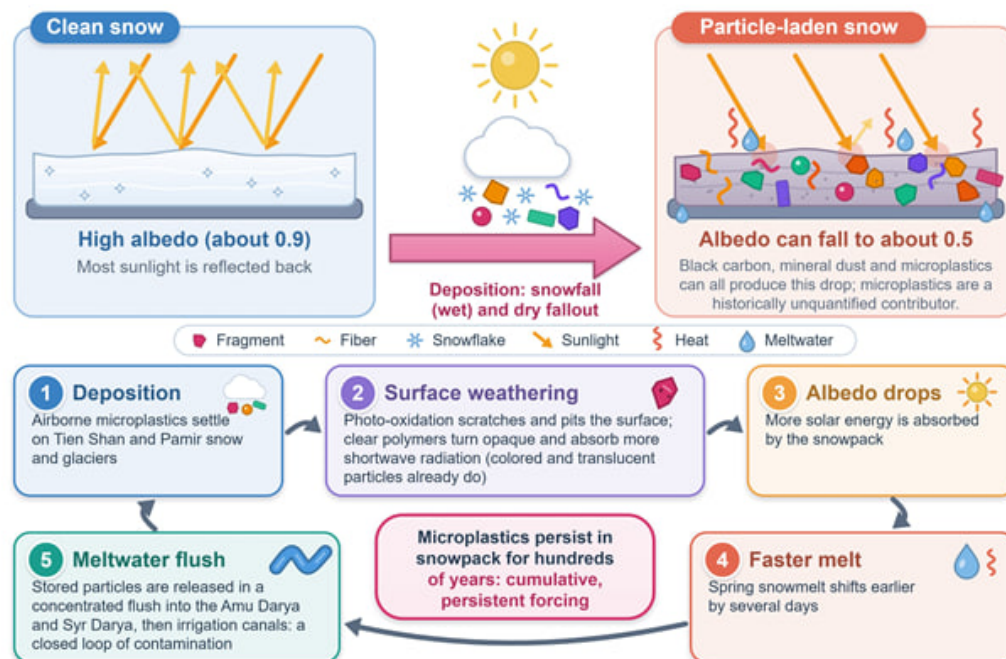


Figure 3. Cryosphere trap and albedo feedback. Particle enrichment lowers snow albedo, which increases absorption of solar energy and accelerates melt. Earlier melt releases stored microplastics in a concentrated flush into river basins and irrigation systems.

3.3.3 Hydrological Impacts: The Amu Darya and Syr Darya Basins

The faster melting of the Central Asian cryosphere has direct consequences for regional hydrology. The Tien Shan and Pamir supply most of the runoff that sustains the endorheic Aral Sea Basin, mainly through the Amu Darya and Syr Darya [25]. As glaciers retreat [26] and seasonal snowpack melts earlier in spring, with the date of cumulative spring snowmelt moving forward by several days, the microplastics stored in the cryosphere are released in one large, concentrated flush [27].

This sudden flux carries millions of accumulated particles straight into the headwaters of the Amu Darya and Syr Darya [28], [29]. Downstream, in the arid lowlands of Uzbekistan and Kazakhstan, much of the water is diverted for irrigation. Microplastics first delivered by high-altitude air currents are therefore spread over lowland farmland through irrigation canals. The result is a closed loop of contamination that threatens soil health, crop productivity and wider food security [25].

3.4 Identification and Analysis: The Role of LC-MS Systems

Assessing the real ecological and toxicological threat from microplastics in Central Asia requires going beyond particle counts and morphology. Current practice relies mainly on non-destructive spectroscopy, namely micro-Fourier transform infrared (μ -FTIR) and Raman spectroscopy, to obtain particle size and the identity of the core polymer, for example confirming that a particle is polyethylene or polystyrene [17]. Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) adds thermal

degradation profiles that confirm total polymer mass [17]. These methods have a clear limit, though. They generally miss the mobile, chemically active and biologically relevant part of the plastic matrix.

Liquid chromatography coupled to mass spectrometry (LC-MS) fills this gap. High-resolution MS (LC-HRMS) and tandem MS (LC-MS/MS) in particular are the analytical gold standard for the complex mix of toxic additives, residual monomers and degradation oligomers that leach from microplastics into tissues and environmental matrices [30]. Figure 4 outlines a typical workflow.

3.4.1 Matrix Effects and Sample Preparation Efficacy

Accurate LC-MS analysis of trace plastic leachates starts with careful sample preparation. Microplastics recovered from complex matrices such as river sediment, aquatic biota or human blood are usually wrapped in biogenic organic material [1]. A standardized digestion protocol is needed to destroy this interfering matter without damaging the target polymers or stripping their additive cargo too early [31].

Digestion efficiency varies considerably with the reagent. Alkaline digestion with 10% potassium hydroxide (KOH) at moderately elevated temperature (for example 40 °C) works well on biological tissue, with over 90% efficiency and intact primary polymers such as PE, PP and PS, although PET can lose a little mass [32], [33]. Oxidizing agents, in particular 30% hydrogen peroxide (H₂O₂) and Fenton's reagent (a catalyst-driven oxidative solution), can reach efficiencies of up to 92% for both hard and soft tissue. Long exposure to oxidative radicals, however, can change the surface chemistry of the microplastics [34], [35]. After digestion, solid-phase extraction (SPE) or liquid-liquid extraction isolates and concentrates the target additives before injection into the LC-MS system [36], [37].

3.4.2 Targeted Analysis and the Mitigation of Background Contamination

Targeted LC-MS/MS is widely used to quantify known priority endocrine-disrupting chemicals (EDCs) that are deliberately added to plastics, such as bisphenols (BPA, BPS) and phthalate diesters (DEHP, DINP, DIDP) [36], [38]. In multiple reaction monitoring (MRM) mode, modern triple quadrupole instruments are very sensitive and can reach sub-nanogram-per-liter (ng L⁻¹) detection limits in complex matrices [30].

The main difficulty in targeted analysis of such widespread additives is background contamination. LC-MS instruments and laboratories themselves contain plastic parts, including PTFE tubing, plasticized solvent lines and polymeric seals, so procedural blanks often show high baseline levels of phthalates and bisphenols [39], [40]. Reliable, artifact-free quantification therefore needs a strict contamination-control workflow. Its key element is a delay column, also called a hold-back column, installed in the flow path between the mobile phase pumps and the autosampler [39]. The column holds back contaminants that come from the solvents and hardware of the HPLC system, so system-derived noise is separated chromatographically from the analytes in the injected sample. This removes false positives and protects data integrity.

3.4.3 Non-Target Screening (NTS) and the Schymanski Confidence Scale

Targeted LC-MS/MS is highly effective, but it only covers a predefined list of analytes, the "known knowns." Microplastics exposed to harsh conditions, such as the intense photo-oxidation on Central Asian glaciers, release thousands of uncharacterized transformation products, new oligomers and degradation artifacts [41]. To find these "unknown unknowns," analysts use non-target screening (NTS) with LC-HRMS, typically on Time-of-Flight (ToF) or Orbitrap mass analyzers that reach mass accuracy below 2 ppm [18], [42].

NTS workflows produce complex, high-dimensional datasets with thousands of unique mass-to-charge (*m/z*) features [41]. To report how confident one can be in the

structure assigned to an unknown feature, the field relies on the Schymanski confidence scale [43]. This five-level hierarchy governs structure elucidation in HRMS (Table 3).

Table 3. Schymanski confidence levels for structure elucidation in LC-HRMS non-target screening.

Schymanski Level	Identification Status	Analytical Evidence Required
Level 1	Confirmed Structure	MS, MS/MS fragmentation, and Retention Time (RT) exactly match an authentic, pure reference standard.
Level 2a	Probable Structure (Library Match)	Strong MS/MS fragmentation spectra uniquely matching a highly curated spectral library.
Level 2b	Probable Structure (Diagnostic)	Diagnostic fragmentation evidence sufficient to propose a specific structure, without a library match.
Level 3	Tentative Candidate	Evidence supports a specific class of compounds or a substructure, but the exact isomer remains indistinguishable.
Level 4	Unequivocal Molecular Formula	Isotope patterns and exact mass accuracy confirm the molecular formula, but no structural fragmentation data exists.
Level 5	Exact Mass of Interest	Only the exact mass (m/z) is known; the chemical formula and structure remain entirely unassigned.

Using LC-HRMS NTS guided by the Schymanski scale, researchers have shown that photochemical weathering of polyurethane and elastomeric microplastics produces thousands of unique chemical features, many of them highly mobile and bioavailable in water [41]. Applying the framework systematically lets analysts decode the chemical mixture that leaches from secondary microplastics as they pass from the Central Asian cryosphere into downstream drinking water supplies.

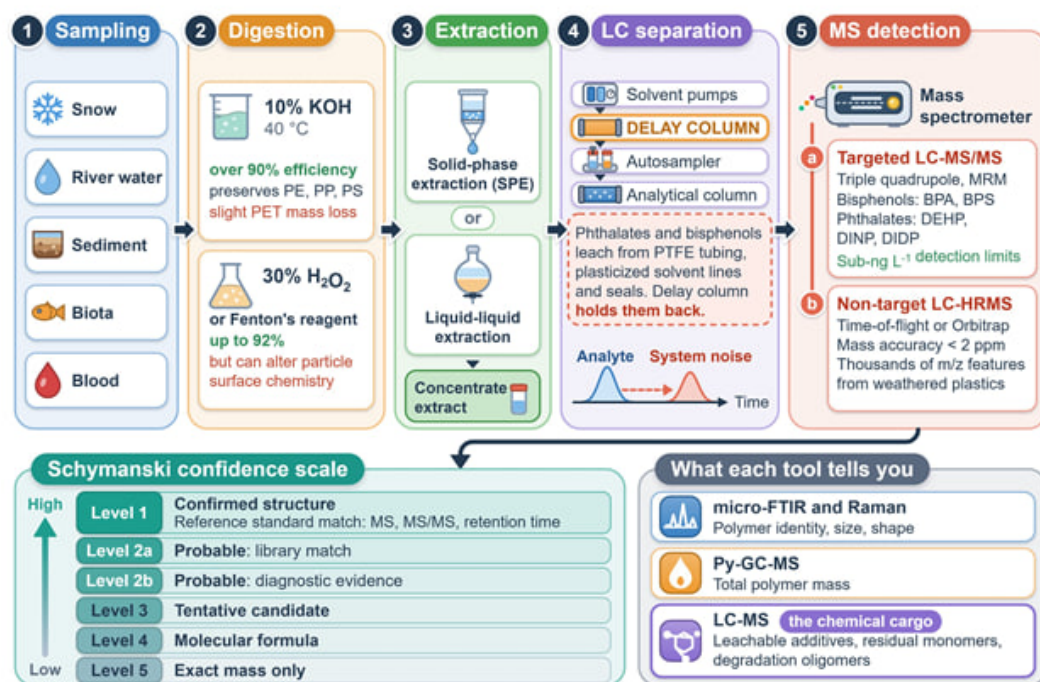


Figure 4. LC-HRMS workflow for characterizing microplastic-derived chemicals, from sampling and digestion to extraction, delay-column chromatography, targeted and non-target mass spectrometry, and reporting with the Schymanski confidence scale.

3.5 Impacts on Human Health

Microplastics are found in atmospheric fallout and in key water systems, so human exposure, mainly through chronic ingestion and inhalation, is essentially unavoidable [1], [44]. Recent biomedical and toxicological work has changed how we view them. They are not inert particles that are simply excreted, and they are not confined to the lining of the gastrointestinal tract. They behave as internal pollutants that can disrupt biology in organs far from the gut [1], [45].

3.5.1 Bioaccumulation Across Biological Barriers

Whether a synthetic particle can cross an epithelial barrier depends strongly on its size, shape and surface chemistry [46]. Nanoplastics (<1 µm) and the smallest microplastics can pass through the intestinal epithelium and the alveolar-capillary barrier of the lung [47], [48].

Once in the circulation, particles accumulate in highly vascularized tissue, and several key studies have now measured plastic particles inside the human body. Leslie *et al.* (2022) provided the first clear evidence of microplastics in human whole blood. Using pyrolysis-GC/MS, they detected quantifiable amounts (averaging 1.6 µg/mL) of PET, PE and PS in 77% of healthy adult donors [49]. Jenner *et al.* later used µFTIR spectroscopy to find microplastics deep in the lower regions of living human lung tissue, which supports inhalation as an exposure route for airborne particulate matter [50]. Ragusa *et al.* isolated microplastics from human placenta, which suggests that maternal exposure carries over to the fetus, with unquantified implications for early developmental toxicity [51]. Figure 5 summarizes the tissue burdens reported in humans.

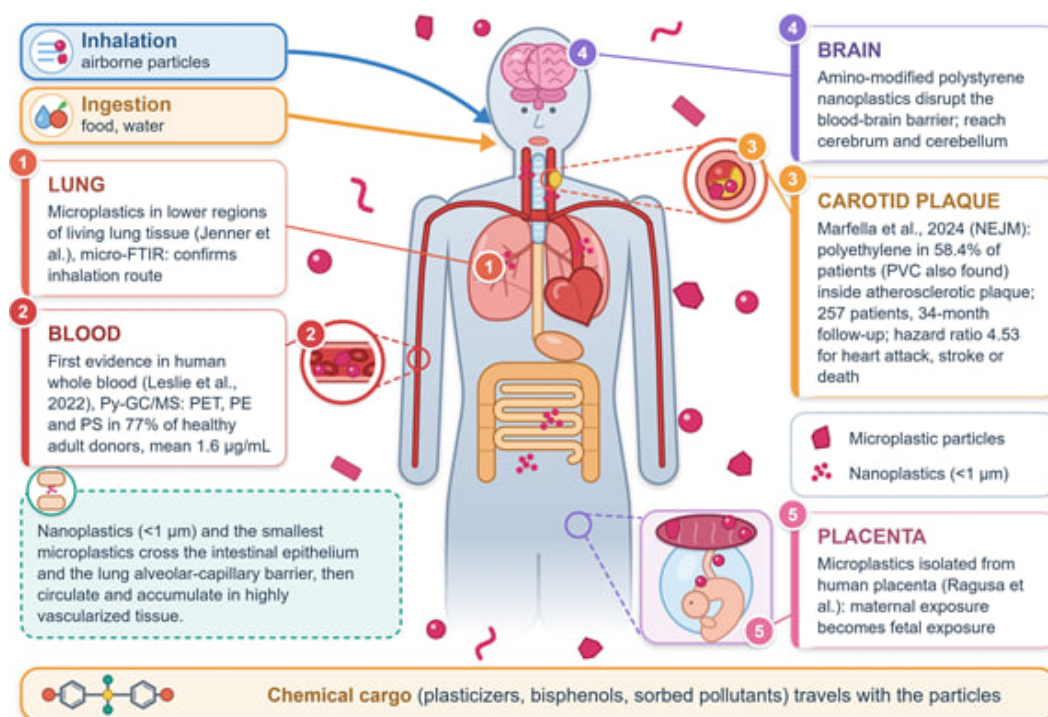


Figure 5. Exposure routes and tissue burdens of microplastics in the human body, as reported in the studies discussed in Section 3.5.

The most worrying finding is that nanoplastics can reach the central nervous system (CNS). In vitro and in vivo models show that amino-modified polystyrene nanoplastics (APS-NPs) can disrupt the blood-brain barrier (BBB) [46], [52]. The disruption is linked to activation of the Toll-like receptor 2 (TLR2) and matrix metalloproteinase-9 (MMP9) axis. Nanoplastic exposure triggers the TLR2/MMP9 pathway in endothelial cells, and MMP9 then degrades the tight junction proteins Occludin and ZO-1 [53]. The loss of tight junctions weakens the structural integrity of the BBB and lets particles keep entering and accumulating in the cerebrum and cerebellum, with possible neuroinflammation, oxidative stress and long-term neurodegeneration [53], [54].

3.5.2 The “Trojan Horse” Vector Effect

The toxicity of microplastics does not come from the particle alone. They are also efficient chemical carriers, a phenomenon called the “Trojan Horse” effect [55]. Microplastics, especially the dominant polyolefins PE and PP, are hydrophobic and therefore strong sorbents for persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs, for example benzo[a]pyrene), pesticides and heavy metals in the surrounding environment [1], [56].

Partitioning of pollutants onto the particle surface is driven mainly by hydrophobic interactions, and the equilibrium distribution coefficient (K_d) correlates closely with the aromaticity of the polymer and the polarity index of the specific plastic [57]. As microplastics move down the intensively farmed Amu Darya and Syr Darya basins, their surfaces concentrate legacy pesticides (for example lindane and DDE) and industrial heavy metals from the surrounding environment [25], [58].

After ingestion, the microplastic enters the very different environment of the gastrointestinal tract, where gastric acid, lipids and bile salts change the chemical fugacity and partition coefficients [1]. This promotes rapid desorption of the chemical cargo and delivers concentrated doses of toxins to the highly permeable gut epithelium [59], [60]. How much this dietary route matters statistically, compared with the natural background biomagnification of hydrophobic chemicals through ordinary lipid pathways, is still debated, particularly around the fugacity models developed by

Koelmans [61], [62]. For intentionally added polymer additives, though, most authors regard the Trojan Horse effect as an efficient delivery mechanism that can bring endocrine-disrupting chemicals straight into systemic circulation [1].

3.5.3 Systemic Toxicity and Cardiovascular Pathogenesis

Once internalized, the particles and their chemical leachates (which LC-MS profiling can map) set off a cascade of cellular toxicity, mainly oxidative stress, formation of reactive oxygen species (ROS) and sustained local inflammation [63]–[66].

The strongest clinical evidence of systemic toxicity in humans comes from Marfella *et al.* (2024), a widely cited prospective study in the New England Journal of Medicine. The authors studied patients undergoing carotid endarterectomy for asymptomatic carotid artery disease. With pyrolysis-GC-MS, stable isotope analysis and high-resolution electron microscopy, they detected polyethylene (in 58.4% of patients) and polyvinyl chloride (PVC) microplastics inside the excised atherosclerotic plaques [67]. Figure 6 summarizes the mechanisms discussed in this section.

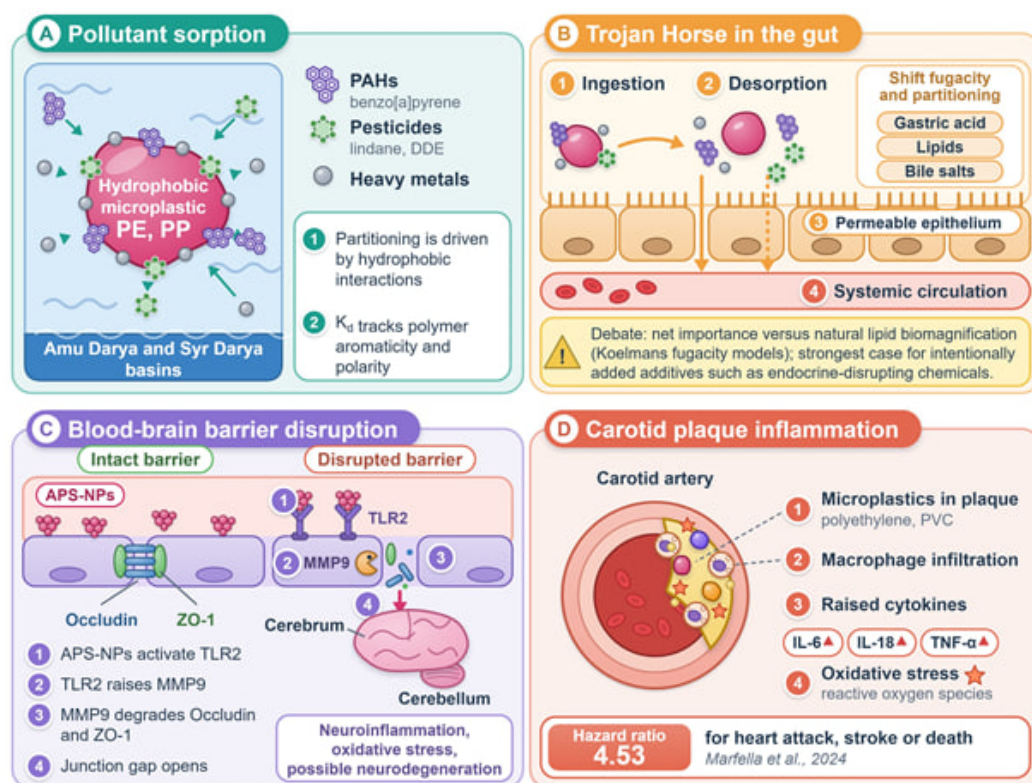


Figure 6. Mechanisms of microplastic toxicity discussed in Section 3.5: pollutant sorption and Trojan Horse transport (A, B), blood-brain barrier disruption through the TLR2/MMP9 axis (C), and vascular inflammation in carotid plaque (D).

The particles appeared to be biologically active. Plaques that contained plastic showed much more macrophage infiltration and clearly higher levels of the inflammatory markers interleukin-6 (IL-6), interleukin-18 (IL-18) and tumor necrosis factor-alpha (TNF- α) [67]. During a 34-month follow-up of 257 patients, those with microplastics detected in their carotid plaque had a hazard ratio of 4.53 for a composite of myocardial infarction, stroke or death from any cause, compared with patients without detectable plastic in the plaque [67]. The study is observational, so it shows an association and cannot by itself prove causation. Even so, it moves microplastics from an abstract environmental hazard toward a plausible, independent contributor to serious cardiovascular disease [68], [69].

3.6 Mitigation, Policy, and Future Perspectives

Tackling microplastics in Central Asia needs coordinated action across analytical chemistry, environmental monitoring and transnational governance.

3.6.1 Analytical Standardization Priorities

The first scientific priority is to standardize analytical methods. The rapid worldwide growth of microplastic research has produced a fragmented set of sample-preparation protocols, digestion efficiencies and detection thresholds [36]. Moving from isolated exploratory studies to monitoring that can support regulation requires harmonized LC-MS workflows. These should include mandatory reporting of procedural blank contamination, routine use of delay columns for all targeted additive analyses, and consistent application of the Schymanski confidence scale when reporting untargeted NTS results [39]. Without such quality assurance and quality control (QA/QC) frameworks, exposure assessments and the epidemiological risk estimates built on them remain open to analytical false positives.

3.6.2 Regional Solutions and Transboundary Governance

Environmental policy in Central Asia has to reflect the transboundary nature of air transport and river flow. Preventing secondary microplastic formation calls for large, coordinated investment in regional solid waste infrastructure, especially the clean-up of unmanaged landfills and a phase-out of the degradable polyethylene mulching films widely used in the Aral Sea Basin [11], [70].

Regional cooperation is also needed to monitor atmospheric pollution and glacier health. Central Asian states, with support from international environmental bodies, should expand cryospheric monitoring networks to track the atmospheric flux of microplastics into the Tien Shan and Pamir. Climate policy should treat these particles not only as toxic agents but also as a thermodynamic forcing that may speed up the loss of regional water security [3].

3.6.3 Future Research Trajectories

Future toxicology should focus on the chronic, low-dose, long-term effects of highly weathered nanoplastics and their mixed chemical leachates on human organ systems. A high priority is *in vivo* work on the neurotoxic effects of blood-brain barrier disruption through the TLR2/MMP9 axis, aimed at establishing dose-response relationships for neurodegeneration [53]. Larger epidemiological studies should also include diverse populations across Central Asia and should link specific contamination routes, such as irrigation with microplastic-laden glacial meltwater, to regional health outcomes and cardiovascular disease rates.

4. Conclusion

Microplastic pollution in Central Asia is not just a regional echo of the much-publicized marine crisis. It is a local atmospheric and cryospheric problem with direct consequences for regional hydrology, agricultural stability and human health. The “silent snowfall” of airborne microplastics onto the glaciers of the Tien Shan and Pamir may act as an accelerant of melting, putting at risk the water security of the Amu Darya and Syr Darya basins while sending a steady downstream flux of toxic polymers to densely populated agricultural and urban areas.

A pollution matrix this complex calls for sophisticated analytical tools. LC-MS is an essential technology here: it looks past the inert polymer to quantify the toxic, mobile additives and degradation products, using identification frameworks such as the Schymanski scale. Evidence that plastic particles accumulate in human blood, lungs, placenta and atherosclerotic plaques, that nanoplastics can breach the blood-brain barrier in experimental models, and that plaque-embedded plastic is associated with cardiovascular events and inflammation, makes action more urgent. Reliable,

standardized identification of both the physical particle and its chemical cargo is the necessary first step toward understanding, reducing and eventually ending the quiet public health problem that microplastics pose to Central Asia and beyond.

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