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Ecological Risks of Plastic Pollution and Biodegradable Alternatives in Wild Medicinal Plant Habitats: A Review

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ABSTRACT

Plastic pollution constitutes one of the most pervasive and ecologically consequential contaminants in contemporary terrestrial environments. This review examines the ecological risks posed by both conventional and biodegradable plastics to wild medicinal plant habitats a category of ecosystem largely overlooked in the plastic pollution literature despite its exceptional biological diversity and pharmacological significance. Drawing on published evidence across soil ecology, ecotoxicology, pollinator biology, and food web dynamics, this synthesis evaluates the mechanisms by which microplastics degrade soil physical structure, disrupt microbial community composition, impair mycorrhizal associations, reduce pollinator fitness, and propagate through terrestrial food chains. Key findings indicate that: (i) microplastic accumulation in terrestrial soils measurably reduces aggregate stability, water holding capacity, and mycorrhizal fungal abundance in ways directly detrimental to plant establishment and secondary metabolite biosynthesis; (ii) biodegradable polymers—including polylactic acid (PLA) and poly(butylene adipate-co-terephthalate) (PBAT) persist as secondary microplastic fragments under ambient field conditions, producing ecotoxicological effects qualitatively comparable to those of conventional polymers; and (iii) ecologically sensitive wild medicinal plant habitats in India, particularly those in biodiversity hotspots coinciding with high plastic waste loading, are exposed to compounding contamination risks that current regulatory frameworks fail to address. The review proposes a multi-tiered bioindicator framework for in situ evaluation of plastic safety in these habitats and identifies three priority areas for research and policy intervention: mandatory field-condition biodegradability testing, biomonitoring within designated conservation zones, and habitat-specific producer responsibility legislation.

Keywords: microplastics; biodegradable polymers; soil ecology; ecosystem function; wild medicinal plants; bioindicators; India

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1. Introduction

Since industrial-scale production began in the 1950s, approximately 8,300 million metric tonnes of virgin plastic have been manufactured worldwide, of which an estimated 79% has accumulated in landfills or the open environment (Geyer et al., 2017). At current production trajectories, that total may approach 12,000 Mt by 2050—a scale of environmental loading whose ecological consequences remain incompletely characterised. The concept of microplastic contamination entered scientific discourse with Thompson et al. (2004), who identified widespread accumulation of plastic fragments smaller than 5 mm in marine coastal sediments. Two decades of subsequent research have established that microplastics permeate all environmental compartments, from ocean trenches and polar ice sheets to freshwater bodies, the atmosphere, and terrestrial soils. A critical reorientation of the field was initiated by Rillig (2012), who observed that microplastic stocks in terrestrial soils may be four to twenty-three times greater than those in the oceans, suggesting that the prevailing marine focus of the discipline provides an incomplete basis for ecological risk assessment.

Despite this recognition, terrestrial microplastic research has remained concentrated in agricultural and urban soil systems, largely overlooking wild, unmanaged ecosystems of high conservation value. Wild medicinal plant habitats—encompassing forest margins, riparian corridors, grasslands, wetland edges, and montane zones—sustain some of the highest plant diversity on Earth and disproportionately overlap with globally recognised biodiversity hotspots. The species they support are embedded within tightly coupled ecological webs: germination depends on fine-textured, mycorrhizally active soils; reproduction depends on insect pollinators with precise foraging ecology; and population persistence depends on seed dispersers and soil engineers whose functional roles are difficult or impossible to substitute. Each of these ecological dependencies appears, on the basis of available evidence, to be susceptible to disruption by plastic contamination.

A critical gap exists in the current literature: no published review has integrated the evidence from soil ecology, ecotoxicology, pollinator biology, and food web science to assess how microplastic pollution including that derived from biodegradable alternatives—may specifically threaten the ecological integrity of wild medicinal plant habitats. Existing syntheses have addressed terrestrial microplastic effects in agricultural soils (Horton et al.,

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2017; Mo et al., 2023) or freshwater systems (Carbery et al., 2018), but the conservation ecology of unmanaged medicinal plant habitats has not been examined as a discrete focus. Furthermore, despite India's status as both a leading contributor to global plastic waste (Jambeck et al., 2015) and a centre of extraordinary medicinal plant diversity, these two intersecting crises have not been evaluated within a unified analytical framework. This review addresses both gaps by synthesising published evidence to characterise the mechanisms of plastic-mediated ecological disruption in these habitats and by critically evaluating the extent to which biodegradable plastics represent a substantive or merely nominal improvement under ambient field conditions.

A further argument, developed across multiple sections, concerns the environmental performance of so-called biodegradable plastics. Despite regulatory endorsement and widespread commercial promotion, the degradation performance of PLA, PBAT, and most starch-based blends under ambient field conditions appears inadequate, potentially generating persistent secondary microplastic fragments with ecotoxicological properties qualitatively similar to those of conventional polymers (Dissanayake et al., 2024; Bläsing & Amelung, 2023). The distinction between certified composting performance and real-world environmental behaviour represents a central policy failure that this review addresses directly.

2. Literature Search Methodology

A systematic literature search was conducted across four major electronic databases: Web of Science, PubMed, Scopus, and Google Scholar. The search was restricted to peer-reviewed publications in English published between 2004 and 2025, with 2004 selected as the start year to coincide with Thompson et al.’s (2004) foundational characterisation of environmental microplastics. Search strings employed Boolean combinations of the following terms: “microplastics,” “plastic pollution,” “biodegradable plastics,” “PLA,” “PBAT,” “PHA,” “soil ecology,” “terrestrial ecosystems,” “medicinal plants,” “pollinators,” “earthworms,” “mycorrhizal fungi,” “trophic transfer,” “bioindicators,” and “India.” Reference lists of retrieved articles were additionally hand-searched for relevant primary studies. Institutional reports from WHO, FAO, and IUCN were included where they provided foundational conservation data unavailable in the peer-reviewed literature.

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Studies were included if they: (i) provided quantitative or systematic evidence of microplastic presence or ecological effects in terrestrial or soil environments; (ii) examined the ecotoxicological effects of conventional or biodegradable microplastics on soil fauna, flora, or microbial communities; or (iii) addressed the ecological characteristics of wild medicinal plant habitats in relation to anthropogenic contamination. Studies were excluded if they were opinion pieces without primary data, focused exclusively on marine or freshwater systems with no demonstrated relevance to terrestrial ecosystems, or were available only as conference abstracts without accompanying peer-reviewed publications. Approximately 28 primary empirical studies and five supplementary institutional reports were synthesised in this review. Where direct empirical evidence pertaining to wild medicinal plant habitats was absent, ecological extrapolation from analogous systems is explicitly identified as such throughout the text.

3. Plastic Pollution

3.1 Production Trajectories and Environmental Loading

Global plastic production reached approximately 380 million metric tonnes per year by 2015 and has continued to increase (Geyer et al., 2017). Single-use packaging constitutes the largest sector by mass and, because the vast majority of manufactured plastic neither biodegrades under ambient conditions nor re-enters productive material cycles, it accumulates progressively in the environment. Jambeck et al. (2015) estimated that between 4.8 and 12.7 million metric tonnes of plastic entered the ocean from coastal populations in 2010 alone, representing a lower-bound indicator of terrestrial plastic loading, given that marine-destined material first transits land environments. Terrestrial retention is substantially greater: Horton et al. (2017) estimated that European terrestrial environments may retain four to twenty-three times more microplastic than they export to adjacent marine systems, positioning soil as the dominant global plastic sink by volume.

Pathways of plastic entry into terrestrial ecosystems are diverse and concurrent. Agricultural plastic mulch films, irrigation infrastructure, and greenhouse covers constitute direct point-source inputs, while sewage sludge applied as agricultural amendment may introduce an estimated 63,000–430,000 tonnes of microplastics annually to European agroecosystems

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alone (Nizzetto et al., 2016). Atmospheric deposition is documented to deliver microplastic fibres and fragments to remote and montane areas well beyond direct emission sources—a pathway of particular relevance to high-altitude medicinal plant habitats. Surface runoff from urban and agricultural land transports both macroplastic debris, which fragments in situ, and pre-formed microplastics into riparian margins and forest edges. Seasonal flooding concentrates and redistributes plastic debris with particular efficiency, depositing material in low-lying zones that frequently harbour ecologically sensitive plant communities.

In the Indian context, plastic waste generation and environmental loading represent a crisis of particular scale and urgency. Jambeck et al. (2015) ranked India among the highest-volume contributors to mismanaged plastic waste globally. Inadequate waste collection infrastructure in rural and tribal areas—which are frequently proximate to ecologically important habitats—combined with the seasonal amplification of debris transport during monsoon flooding, may create conditions under which wild medicinal plant habitats receive substantial plastic inputs from both proximate and distant sources. The geographic superimposition of India's highest plastic waste emissions on centres of medicinal plant diversity is not coincidental; it is the core conservation problem this review addresses.

3.2 Microplastic Characterisation in Soil Environments

Microplastics in terrestrial environments are characterised by considerable diversity in polymer type, particle size, morphology, and surface chemistry. Common polymer types detected in soil include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC), alongside more recently identified biodegradable types including PLA and PBAT (Han et al., 2024). Particle morphologies range from fragments and foams to films and—most abundantly in many surveys—fibres of synthetic textile origin introduced through laundry effluent and atmospheric fallout. Importantly, fibres produce qualitatively distinct alterations of soil porosity and water retention that differ mechanistically from the effects of spherical or angular fragment-type particles (de Souza Machado et al., 2019), underscoring the need to differentiate among microplastic types rather than treating them as a uniform contaminant class. Polymer identification in environmental matrices relies principally on attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) and Raman spectroscopy, whose

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adoption in field surveys has substantially expanded the geographic and taxonomic scope of contamination documentation.

Singh et al. (2024) conducted one of the first systematic characterisations of terrestrial microplastic contamination in Central India, detecting multiple polymer types in agricultural and recreational soils of Indore, Madhya Pradesh. While their ecological risk assessment classified current contamination as low, the authors cautioned explicitly that the persistent nature of microplastics—accumulating over decades without active remediation—necessitates immediate monitoring frameworks. Crucially, a classification of “low risk” based on current concentrations does not adequately account for long-term accumulation dynamics or the ecological sensitivity of adjacent habitats—a limitation that Singh et al. (2024) acknowledge and that warrants emphasis in interpreting their findings. The proximity of these agricultural landscapes to forest corridors supporting wild medicinal plant diversity in the Satpura Range and adjacent zones amplifies the conservation relevance of this baseline finding.

4. Ecological Impacts of Plastic Pollution on Soil Systems

4.1 Physical Disruption of Soil Structure

Soil physical structure—the arrangement of mineral particles, organic matter, and pore spaces into aggregates of varying stability—governs root penetration, water infiltration, gas exchange, and the spatial organisation of the microbial community. De Souza Machado et al. (2019), working with four polymer types in mesocosm experiments at environmentally relevant concentrations, demonstrated polymer-specific alteration of soil bulk density, water holding capacity, hydraulic conductivity, and aggregate stability. Polyester fibres produced the most pronounced reduction in water holding capacity and the greatest increase in evapotranspiration, effects the authors attributed to physical disruption of capillary pore networks within aggregates. These findings, though generated under controlled conditions, have direct ecological relevance: in seasonally dry or shallow-soiled wild habitats, even modest reductions in water holding capacity may determine whether seedling establishment succeeds or desiccation mortality occurs.

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Han et al. (2024) extended this analysis to the aggregate scale—a methodological choice that better reflects the heterogeneous microenvironment experienced by soil biota—and found that both conventional and biodegradable microplastics disrupted soil aggregate distribution and microbial community composition to a broadly comparable degree. This finding carries a direct policy implication: the physical effects of microplastics on soil structure appear intrinsic to the presence of polymer particles, rather than uniquely attributable to the chemical leaching associated with conventional petrochemical plastics. Together, de Souza Machado et al. (2019) and Han et al. (2024) provide complementary evidence across experimental scales. However, both studies employed controlled laboratory or mesocosm conditions; field validation under the heterogeneous conditions of wild habitats remains an important methodological gap that future research should address.

4.2 Soil Microbial Community Disruption

The soil microbial community—encompassing bacteria, archaea, fungi, and protists—mediates nitrogen fixation, phosphorus mineralisation, organic matter decomposition, and plant–mycorrhizal symbioses, constituting the functional engine of soil fertility. Microplastic contamination has been consistently associated with impairment of this community across multiple experimental systems. Baho et al. (2021) documented altered bacterial community diversity, reduction in beneficial functional guilds, and shifts in community metabolic profiles away from nutrient cycling toward stress response pathways. While the majority of these findings derive from laboratory studies or mesocosms rather than field surveys, their consistency across experimental designs and polymer types lends credibility to the inference that the effect is real. Critically, Baho et al. (2021) also highlighted that single-species laboratory assays cannot capture the emergent, non-linear dynamics that arise from species interaction networks in biodiverse habitats—a limitation with direct relevance to the complexity of wild medicinal plant ecosystems.

The ecological significance of mycorrhizal disruption is particularly acute in wild medicinal plant habitats, where species of Withania, Rauvolfia, Nardostachys, Tinospora, and Berberis, among others, depend on arbuscular or ectomycorrhizal partnerships for mineral nutrition in characteristically low-nutrient, undisturbed soils. Microplastic-associated reductions in mycorrhizal fungal abundance—documented at the aggregate scale by Han et al. (2024)—

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may directly threaten the nutritional basis of plant populations for which no manufactured substitute for mycorrhizal services exists in unmanaged habitats. In agricultural systems, fertiliser can compensate partially for mycorrhizal dysfunction; in wild habitats, no such corrective mechanism is available.

Beyond diffuse community effects, the plastisphere—the microbial community colonising plastic surfaces—introduces a qualitatively distinct ecological concern. These communities are enriched in potential pathogen taxa, antimicrobial resistance genes, and biofilm-forming organisms that differ markedly in composition and functional profile from surrounding bulk soil communities (Baho et al., 2021). In wild habitats whose biological integrity is defined by their unmanipulated microbiome, plastisphere colonisation represents a form of persistent biological alteration. Baho et al. (2021) framed this broader problem as one of "ecological surprise"—the elevated probability of threshold-crossing, non-linear ecosystem responses emerging from the high persistence, interactive complexity, and contaminant-carrying capacity of microplastics. This framing is especially pertinent in wild medicinal plant habitats, where the absence of active management means that ecological deterioration, once initiated, is unlikely to be detected or reversed before community composition has fundamentally shifted.

4.3 Chemical Toxicity: Additives and Sorbed Contaminants

Conventional plastics are chemical mixtures rather than pure polymers. Intentionally added substances include phthalate ester plasticisers, polybrominated diphenyl ether flame retardants, UV stabilisers, antioxidants, and pigments; non-intentionally added substances arise as degradation or reaction by-products during manufacture and environmental weathering. Zimmermann et al. (2021) demonstrated that between 1% and 88% of the chemicals associated with a plastic product may migrate into contact media under realistic use conditions, and that the structural identity of the majority of detected migrating chemicals remained uncharacterised—a toxicological blind spot of considerable regulatory concern. Phthalates and bisphenol A (BPA) have been extensively studied as endocrine-disrupting compounds capable of interfering with hormonal systems in invertebrates and vertebrates at ecologically relevant concentrations. In the context of soil ecology, phthalate exposure has been shown to reduce earthworm reproductive output and disrupt Rhizobium symbiosis in

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leguminous plants, with downstream consequences for soil nitrogen availability—though it should be acknowledged that dose-response relationships under complex field exposure scenarios remain incompletely defined (Baho et al., 2021).

Microplastics additionally function as environmental vectors for persistent organic pollutants (POPs), heavy metals, and other contaminants sorbed to their surfaces via hydrophobic interactions and electrostatic binding. Carbery et al. (2018), reviewing trophic transfer mechanisms in marine food webs, established that the physical and chemical properties of microplastics—high surface area-to-volume ratio, hydrophobic surface chemistry, and polymer-specific sorption affinity—facilitate co-concentration of polycyclic aromatic hydrocarbons, organochlorine pesticides, and trace metals. While the terrestrial evidence base remains substantially smaller than that for marine systems, Prajapati et al. (2024) confirmed the co-occurrence of microplastics and heavy metals in urban soils of Madhya Pradesh, a region bordering ecologically important Central Indian forest corridors. This finding establishes that co-contaminant vectoring is not a theoretical concern but an empirically confirmed exposure scenario in proximity to key Indian medicinal plant habitats. The transition from soil contamination to faunal and floral effects is examined in the following section.

5. Soil Fauna, Pollinators, and Trophic Food Web Dynamics

5.1 Earthworms: Bioaccumulation and Ecosystem Engineering

No single animal group occupies a more central position in terrestrial soil ecology than earthworms. Through bioturbation, organic matter incorporation, and cast production, they drive soil macroporosity, aggregate stability, and surface-to-subsoil organic matter redistribution—the physical processes that create and maintain the humus-rich, well-structured soils characteristic of productive wild habitats. Samal et al. (2024), in a comprehensive critical review, characterised earthworms as simultaneously functioning as biofilters, bioindicators, bioaccumulators, and biotransformers of microplastics in contaminated soils—a suite of roles that positions earthworm responses as particularly informative and standardisable endpoints for ecological risk assessment in terrestrial systems.

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Quantitative evidence for microplastic concentration across trophic levels in terrestrial food chains was documented in field measurements cited by Baho et al. (2021), where microplastic concentrations rose from 0.87 ± 1.9 particles per gram in bulk soil to 14.8 ± 28.8 particles per gram in earthworm casts, and reached 129.8 ± 82.3 particles per gram in the faeces of surface-feeding birds. The wide standard deviations reported across all three compartments indicate considerable spatial heterogeneity, warranting caution in interpreting these values as precise estimates of biomagnification potential; additional site-level replication is needed before stepwise concentration factors can be treated as robust. At the molecular level, Huerta Lwanga et al. (2017) found that polystyrene microplastics at 0.02% w/w disrupted osmoregulatory metabolism in Eisenia fetida without detectably affecting gut microbiota diversity, suggesting that biochemical toxicity may precede detectable microbial community change and that standard community-level endpoints may underestimate the early biological impact of exposure. Studies examining biodegradable polymers (PLA and PHB) reported significant impairment of earthworm growth and reproductive output at concentrations of 1% w/w over medium-term exposure periods (Gutiérrez-Rial et al., 2025). While these concentrations exceed most current field measurements, the accumulation trajectory of biodegradable microplastics in progressively contaminated landscapes is upward, and the timescale over which ecotoxicologically significant concentrations may be reached is a conservation-critical question rather than a purely theoretical one.

The conservation significance of earthworm impairment in wild medicinal plant habitats is concrete and mechanistically traceable. Earthworm bioturbation is a primary mechanism generating and maintaining the deep humus horizons, mycorrhizally active pore networks, and seed-burial conditions upon which many wild medicinal species depend for establishment and persistence. A reduction in earthworm community density, reproductive output, or functional diversity may initiate a cascade of soil degradation—reduced aggregate turnover, declining organic matter incorporation, and progressive compaction that degrades microhabitat conditions in ways potentially synergistic with canopy disturbance or hydrological alteration. This cascading pathway is mechanistically plausible and grounded in well-established soil ecological principles, though direct empirical validation in wild medicinal plant habitat contexts has not yet been undertaken. The transition from soil-

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dwelling fauna to aerial pollinators represents a further critical pathway through which plastic contamination may indirectly impair plant reproductive success.

5.2 Pollinator Impairment and Reproductive Consequences for Medicinal Plants

The reproductive biology of wild angiosperm medicinal species is overwhelmingly dependent on animal pollination. This dependency is especially pronounced in families including Apiaceae, Asteraceae, Lamiaceae, Ranunculaceae, Zingiberaceae, and Orchidaceae, all of which contribute pharmacologically significant wild species, and none of which could sustain genetically viable populations in the sustained absence of effective pollinator communities. Any contaminant that degrades pollinator performance therefore acts as an indirect but potentially severe threat to medicinal plant reproductive viability, genetic connectivity, and long-term population persistence. The pathway linking soil contamination to plant reproductive failure through pollinator impairment is one of the most ecologically distinctive features of microplastic risk in medicinal plant habitats and remains insufficiently recognised in the current literature.

Al Naggar et al. (2024) reviewed the available evidence on microplastic impacts on honey bees (Apis mellifera), documenting reduced feeding rates, impairment of associative learning and foraging memory in workers—with direct consequences for floral fidelity and colony homing success—altered expression of genes involved in antioxidative defence, detoxification, and innate immunity, and increased susceptibility to viral infections at the colony level. Li et al. (2024), in a systematic review and meta-analysis covering terrestrial insects more broadly, confirmed significant negative effects of microplastic exposure across taxa, with effect sizes scaling with polymer concentration and exposure duration. Taken together, Al Naggar et al. (2024) and Li et al. (2024) provide complementary evidence at the species-specific and cross-taxon scales, respectively, lending robustness to the conclusion that microplastic exposure is associated with ecologically meaningful pollinator impairment. A preprint by Balzani et al. (2024) reported synergistic toxicity when bees were exposed to multiple polymer types simultaneously a scenario more representative of real-world environmental conditions than single-polymer laboratory assays—though this work has not yet undergone independent peer-reviewed validation and should be interpreted with appropriate caution. Beyond physiological impairment, de Souza Machado et al. (2018) noted

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that microplastic particles overlap in size with pollen grains across many angiosperm taxa, raising the possibility that microplastics may competitively obstruct stigmatic pollen deposition and thereby reduce fertilisation rates in wild plant populations—a mechanism requiring targeted empirical investigation.

5.3 Trophic Transfer and Seed Dispersal Disruption

Carbery et al. (2018) documented trophic transfer of microplastics and co-sorbed contaminants across food web levels in marine systems, establishing mechanistic principles—concentration through selective ingestion, differential elimination efficiency, and hydrophobic co-contaminant accumulation that are plausibly applicable to terrestrial food chains, although direct evidence from terrestrial systems is substantially less extensive. In wild medicinal plant habitats, the relevant trophic pathways connect soil microplastics through earthworms to surface-foraging birds and small mammals, through contaminated plant material to herbivorous insects and vertebrates, and through fruit-eating frugivores to the seed-dispersal guilds upon which plant population spatial dynamics depend. Baho et al. (2021) identified food web complexity as a likely multiplier of plastic pollution risk in biodiverse terrestrial ecosystems, noting that species interaction networks may generate numerous indirect pathways through which contaminant effects propagate to organisms that have never directly contacted plastic a phenomenon particularly relevant to the intricate ecological webs of wild medicinal plant habitats.

Seed dispersal by frugivorous vertebrates represents a particularly important and essentially unstudied pathway in this context. Frugivores that regularly ingest microplastic-contaminated plant material or soil may exhibit altered foraging behaviour, disrupted spatial memory, or impaired gut function, with potential consequences for the distance and directionality of seed deposition. For wild medicinal plant species already fragmented across degraded habitat mosaics, altered seed dispersal patterns could progressively shift population distributions toward areas of lower habitat quality, reduce genetic connectivity among remnant populations, and accelerate local extinction debt. This pathway constitutes a tractable priority for future empirical investigation and represents a domain where targeted research could directly inform conservation management of medicinally important habitats.

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6. Biodegradable Plastics: Environmental Performance, Limitations, and Polymer-Specific Profiles

6.1 The Gap Between Certification and Field Reality

The commercial expansion of biodegradable plastics represents a genuine policy and industry response to the persistence problem of conventional polymers, and this effort warrants acknowledgement before its limitations are examined. Under certified industrial composting conditions—temperatures of 55–60°C, controlled aeration, and managed microbial communities—PLA and PBAT achieve substantial mineralisation within 90–180 days and satisfy EN 13432 and ASTM D6400 certification standards. Mo et al. (2023) reviewed biodegradable plastic behaviour in agricultural soil ecosystems and identified conditions under which polyhydroxyalkanoates (PHAs) may achieve meaningful ambient-temperature degradation with reduced long-term accumulation risk compared with polyethylene mulch films. These findings indicate that biodegradable plastics are not uniformly equivalent to conventional alternatives; their environmental performance depends critically on the conditions of the disposal environment.

However, the gap between certified composting performance and in situ environmental behaviour in wild habitats constitutes the central policy problem revealed by this body of literature. Dissanayake et al. (2024) measured degradation of PBAT and PLA under controlled soil incubation: after 33 weeks at 25°C—approximating mean temperate soil temperature—only 2.3% of PBAT and 1.7% of PLA had mineralised. At 58°C (approximating industrial composting conditions), degradation rose to 9.2% and 6.1%, respectively. These data indicate that at field-relevant temperatures, both polymers may persist largely intact over the timescale of a growing season, generating secondary microplastic fragments as surface weathering proceeds. Bläsing and Amelung (2023), in a comprehensive critical review encompassing both waste management and open environmental contexts, reached the same conclusion and identified the absence of standardised in situ test methods as the critical regulatory gap enabling misleading product claims. The implication for wild medicinal plant habitats is unambiguous: materials commercially described as "biodegradable" that enter these habitats through atmospheric fallout, hydrological transport, or unregulated disposal may persist as microplastic pollutants

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for months to years, exerting physical ecological effects indistinguishable from those of conventional polymer fragments.

6.2 Ecotoxicological Evidence for Biodegradable Polymer Impacts

The assumption that biodegradable polymers are inherently biologically safer than conventional plastics is challenged by the available, if still limited, evidence. Han et al. (2024) demonstrated that biodegradable microplastics disrupted soil aggregate structure and microbial community composition to a degree statistically comparable to conventional microplastics—a finding suggesting that physical ecological effects are more closely related to particle presence per se than to polymer chemistry. PLA microplastics have been associated with chromosomal abnormalities and disrupted mitosis in plant cells, and with abnormal embryogenesis in marine invertebrate model organisms (Chen et al., 2024). Although the generalisability of these findings to terrestrial plant species under field conditions has not been established and requires further investigation, they indicate that biodegradable polymer fragments should not be assumed to be biologically inert. PBAT degradation produces terephthalic acid as a hydrolysis product—a compound with documented aquatic toxicity—though its ecological fate in terrestrial soils and its terrestrial toxicity profile require further characterisation before risk conclusions can be drawn.

Earthworm ecotoxicology provides the most directly applicable terrestrial dataset. Gutiérrez-Rial et al. (2025) reported that exposure to PLA and PHB microplastics at 1% w/w significantly impaired earthworm growth and reproductive output over medium-term exposure periods. While these concentrations exceed most current field measurements, the upward accumulation trajectory of biodegradable microplastics in progressively contaminated habitats makes this a question of conservation-critical timing rather than theoretical irrelevance. Crucially, the ecotoxicological evidence base for biodegradable polymers remains substantially smaller than that for conventional plastics, meaning that apparent similarities in effect magnitude may partly reflect insufficient statistical power to detect differences rather than confirmed equivalence. This evidential asymmetry demands continued precautionary assessment rather than premature conclusions of safety.

6.3 Polymer-Specific Environmental Profiles

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Meaningful environmental evaluation of biodegradable plastics requires differentiation among polymer types whose behaviour in soil varies substantially. Polyhydroxyalkanoates (PHAs), including polyhydroxybutyrate (PHB), are produced by bacterial fermentation without petroleum-derived components and are degraded in soil and marine environments by diverse microbial communities under ambient conditions. PHAs represent the only certified biodegradable polymer class for which genuine ambient-temperature biodegradation is well-supported outside composting facilities (Bläsing & Amelung, 2023). Their environmental profile is the most favourable of the polymer classes assessed here. However, ecotoxicological datasets for soil fauna and plant communities remain substantially smaller than those for PLA or PBAT, and field-scale validation in wild habitat contexts has not been undertaken. This knowledge gap should not be conflated with demonstrated safety.

Starch-based plastic blends present a more problematic environmental profile. The starch fraction degrades readily under ambient soil conditions, but the synthetic polymer fraction—most commonly polyethylene or polypropylene does not, leaving conventional petrochemical microplastic residues in direct proportion to the synthetic fraction of the original product. The net ecological outcome may therefore be equivalent to direct conventional microplastic deposition; the “biodegradable” label applies to only a fraction of the material. Polybutylene succinate (PBS) occupies an intermediate position: it degrades in soil under a wider range of conditions than PLA or PBAT but substantially more slowly than PHAs, and its ecotoxicological characterisation for soil fauna and plant communities remains incomplete (Bläsing & Amelung, 2023). Policy frameworks that treat all certified biodegradable plastics as a single, interchangeable category obscure these critical differences and may undermine the regulatory incentive to favour genuinely soil-degradable polymers such as PHAs over lower-cost, slower-degrading alternatives such as PLA and PBAT.

7. Wild Medicinal Plant Habitats: Ecological Characteristics and Plastic Vulnerability

7.1 Conservation Significance and Ecological Dependencies

Wild medicinal plant habitats represent some of the most ecologically complex and conservation-critical terrestrial systems on Earth, yet they remain among the least studied in the context of novel anthropogenic contaminants. These habitats overlap disproportionately

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with globally recognised biodiversity hotspots—regions defined by exceptional species richness, high endemism, and acute anthropogenic threat—including the Western Ghats and Sri Lanka, the Himalayas, the Indo-Burma region, and the Eastern Afromontane zone. In India alone, approximately 8,000 plant species are used medicinally, the majority sourced from wild populations growing in forest margins, sacred groves, grasslands, and riparian zones (WHO/IUCN/WWF, 1993). The pharmacological value of these populations depends not only on species presence but on the ecological relationships sustaining secondary metabolite biosynthesis: soil nutrient status, mycorrhizal partnership identity, pollination success, and seed dispersal dynamics all influence phytochemical profiles and population genetic diversity, which together define both medicinal quality and long-term population resilience.

These habitats are simultaneously ecologically productive and disproportionately sensitive to novel persistent contaminants, for reasons that distinguish them from the agricultural systems in which most microplastic ecotoxicology has been conducted. High plant–pollinator co-dependence means that impairment of any component of the pollinator guild may translate into reduced reproductive output across multiple plant species simultaneously. Dependence on mycorrhizal fungi adapted to low-nutrient, undisturbed soil conditions means that microbiome disruption from plastic contamination cannot be mitigated through fertilisation or soil amendment, as is possible in agricultural systems. Deep food web connectivity means that contaminant effects may propagate non-linearly through interaction networks, producing the dynamics that Baho et al. (2021) described as ecological surprise. Unlike managed agroecosystems, which are periodically reset by tillage, chemical inputs, and replanting, wild medicinal plant habitats sustain ecological relationships developed over decades to centuries; their capacity to resist or recover from persistent novel contaminants is essentially uncharacterised and should not be assumed to be high.

7.2 Specific Vulnerabilities: Illustrative Species Analysis

The following species-level analysis is presented as mechanistic inference grounded in documented soil ecological processes, not as a summary of direct empirical evidence. To the authors' knowledge, no published study has examined the effects of microplastic contamination on these specific species under field conditions. The value of this analysis lies

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in making explicit the ecological pathways through which documented soil microplastic effects could translate into species-level conservation risk—thereby identifying research priorities and justifying precautionary management rather than asserting confirmed outcomes. The absence of direct species-specific evidence reflects the broader neglect of this intersection in the ecotoxicological literature and does not constitute evidence of absence of risk.

Withania somnifera (L.) Dunal (ashwagandha; Solanaceae), one of India's most economically and pharmacologically significant adaptogenic plants, illustrates the rhizosphere pathway. In wild populations across dry deciduous forest margins and rocky sub-Himalayan slopes, withanolide biosynthesis the pharmacological hallmark of the species—is understood to depend closely on rhizosphere microbial community composition and arbuscular mycorrhizal fungal (AMF) associations supplying phosphorus and trace elements as biosynthetic co-factors. Based on documented microplastic effects on soil aggregate stability (de Souza Machado et al., 2019) and mycorrhizal fungal abundance (Han et al., 2024), plastic contamination of the characteristically sandy, low-organic-matter soils inhabited by wild W. somnifera may impair both root biomass accumulation and withanolide yield—reducing not only plant productivity but pharmacological potency. This inference is mechanistically grounded but requires empirical validation in this species' specific habitat context.

Rauvolfia serpentina (L.) Benth. ex Kurz (sarpagandha; Apocynaceae), the primary natural source of the antihypertensive alkaloid reserpine and already classified as threatened due to over-collection and habitat loss, inhabits moist tropical forest understories in the Eastern Himalayan foothills and Western Ghats. These populations depend on deep, humus-rich soils maintained by active earthworm bioturbation. Based on the documented impairment of earthworm community function by microplastic exposure (Samal et al., 2024), contamination of these closed-canopy forest soils could plausibly accelerate compaction and organic matter stratification, progressively reducing habitat suitability for a species whose recovery capacity is already constrained by slow growth, late reproductive maturity, and restricted habitat distribution. Again, this pathway is mechanistically plausible but has not been tested in Rauvolfia habitats specifically.

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Nardostachys jatamansi (D.Don) DC. (jatamansi; Caprifoliaceae), an endemic alpine species of the central and eastern Himalaya (3,000–5,000 m elevation), grows in poorly developed, gravelly, low-phosphorus soils where AMF associations are considered obligate for mineral nutrition. This species is simultaneously subject to atmospheric microplastic deposition—a well-documented contamination pathway for high-altitude environments—and may be exposed to declining high-altitude specialist pollinator communities under increasing plastic pollution pressure (Al Naggar et al., 2024; Li et al., 2024). The potential convergence of multiple impairment mechanisms in a species characterised by narrow ecological tolerance creates a plausible multi-stressor risk scenario, though direct evidence from Himalayan medicinal plant habitats has not been reported.

7.3 Contamination Pathways and the Indian Context

Plastic contamination of wild medicinal plant habitats in India appears to occur through several concurrent and partially overlapping pathways. Atmospheric deposition introduces microplastic fibres and fragments to habitats distant from direct emission sources, including the montane environments hosting several endemically important medicinal species. Surface runoff from agricultural and peri-urban land carries both pre-formed microplastics and macroplastic debris into riparian margins and forest edge communities. Seasonal monsoon flooding—India's primary mechanism of landscape-scale debris redistribution—concentrates plastic material in low-lying riparian zones that are ecologically productive and frequently support high medicinal plant diversity.

Amaneesh et al. (2025) provided one of the first peer-reviewed detections of microplastic contamination in agricultural soils directly adjacent to the Western Ghats biodiversity hotspot in Karnataka and Goa, with fibre-dominant assemblages consistent with a synthetic textile input pathway via domestic wastewater disposal. Singh et al. (2024) confirmed multiple polymer types in Central Indian soils adjacent to forest zones with established medicinal plant diversity. Prajapati et al. (2024) documented the co-occurrence of microplastics and heavy metals in urban soils of Madhya Pradesh, a region bordering ecologically important Central Indian forest corridors. Collectively, these three independent Indian studies establish that plastic contamination at the boundaries of key medicinal plant habitats is real and measurable. However, dedicated monitoring within protected areas, wildlife corridors, and

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formally designated medicinal plant conservation zones has not been undertaken and represents an urgent surveillance gap that policy-makers and ecologists should address as a priority.

India’s 2021 Environment (Protection) Amendment Rules, which introduced phased restrictions on specific categories of single-use plastic, represent a meaningful policy step. However, enforcement in rural and tribal areas adjacent to biodiversity corridors remains variable, and the adoption of biodegradable plastic substitutes without mandatory in situ degradation performance standards—as discussed in Section 6—risks replacing one form of habitat contamination with another whose ecological effects, under ambient field temperatures, may not differ substantially.

8. Bioindicator Frameworks for Evaluating Plastic Safety in Wild Habitats

Current regulatory standards for biodegradable plastic certification EN 13432 in Europe and ASTM D6400 in the United States—assess degradation performance and ecotoxicological effects under standardised composting conditions using limited biological test systems, typically plant germination assays and earthworm acute survival tests at concentrated doses. These standards were not designed to evaluate in situ ecological performance in complex, biodiverse, unmanaged habitats and are not adequate for that purpose. Baho et al. (2021) explicitly recommended that terrestrial microplastic research move beyond single-species, short-term laboratory paradigms toward multi-species assemblage studies under realistic field conditions, on the basis that ecological surprises emerging from species interaction networks are invisible to reductive single-organism tests. This recommendation applies with particular urgency to the evaluation of plastic materials likely to enter wild medicinal plant habitats through atmospheric, hydrological, and waste-dispersal pathways.

A multi-tiered bioindicator framework for such habitats should incorporate, at minimum, four assessment components that together capture ecological effects across the principal levels of biological organisation relevant to medicinal plant conservation. At the foundation, soil microbiome diversity and functional profile assessment—using amplicon sequencing to characterise community composition and functional gene arrays to evaluate nitrogen cycling, phosphorus mineralisation, and mycorrhizal fungal community integrity—provides a

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sensitive early-warning signal of ecosystem function disruption before plant-level effects become detectable. The second tier—earthworm survival, reproductive output, and biomarker responses (including coelomocyte immunocompetence, oxidative stress indices, and metallothionein induction) under field-realistic exposure conditions—captures soil engineering consequences of contamination and provides standardised, reproducible metrics amenable to long-term comparative monitoring. The third tier incorporates pollinator behavioural assays using native bee species (Bombus spp. and Xylocopa spp., in preference to the managed honey bee where practicable) to evaluate the indirect plant-reproductive services upon which medicinal plant population viability depends. The fourth tier—sentinel medicinal plant monitoring, tracking germination success, seedling establishment rates, adult plant phytochemical profiles, and seed set across known microplastic-exposed and reference populations—provides the whole-ecosystem outcome indicator that links the preceding mechanistic tiers to the conservation objective.

The design of this framework reflects the principle articulated by Baho et al. (2021) that the burden of demonstrating ecological safety in complex habitats must rest on in situ evidence rather than on standardised composting-condition performance. The current regulatory framework—in which certification of composting-condition performance is sufficient for a material to be commercially described as environmentally benign is not supported by the ecological evidence synthesised here. Its continuation may create conditions under which wild medicinal plant habitats are progressively contaminated by materials whose ecological harmlessness has never been evaluated in the environments they actually enter.

9. Integrated Perspectives

Across the evidence base reviewed in this paper, several convergent findings warrant explicit integration. The physical accumulation of microplastic particles in terrestrial soils irrespective of polymer class is consistently associated with degradation of the biophysical rhizosphere environment, including reduced aggregate stability, diminished water holding capacity, and impaired mycorrhizal fungal abundance (de Souza Machado et al., 2019; Han et al., 2024). These effects are documented across replicated experimental systems and in field surveys from multiple geographic contexts, including India’s agricultural and peri-urban environments adjacent to key medicinal plant habitats (Singh et al., 2024; Prajapati et al.,

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2024; Amaneesh et al., 2025). While direct evidence from wild medicinal plant habitats themselves remains absent, the mechanistic pathways through which these effects would translate to medicinal plant populations are ecologically concrete and traceable.

The chemical dimension of plastic pollution—through leaching of plastic-associated additives and vectoring of sorbed environmental contaminants—operates concurrently with, and potentially synergistically with, the physical effects described above. The structural characterisation of the majority of plastic-associated migrating chemicals remains incomplete (Zimmermann et al., 2021), strengthening rather than undermining the case for precautionary policy, particularly in ecologically sensitive habitats where the consequences of contamination are difficult to reverse once established. The trophic and ecosystem-service dimensions reviewed in Section 5—earthworm impairment, pollinator decline, food web contamination—extend the scope of plastic impacts from the soil compartment to the biotic networks that sustain plant community structure and medicinal plant reproductive biology, producing compound risks that no single-endpoint regulatory assessment can adequately characterise.

The biodegradable plastics discussion requires the particular nuance that the current regulatory framework does not adequately provide. The evidence synthesised here does not support the conclusion that all biodegradable polymers are ecologically equivalent to conventional plastics—PHAs under ambient conditions represent a genuinely distinct and more environmentally favourable case. However, the evidence equally does not support the conclusion that certification as “biodegradable” is equivalent to ecological safety in wild habitats. For PLA and PBAT specifically, field-condition degradation data are consistent across independent research groups: these materials generate persistent secondary microplastics in soil at ambient temperatures, and their ecotoxicological effects on soil organisms show qualitative similarity to those of conventional polymer fragments (Han et al., 2024; Gutiérrez-Rial et al., 2025; Dissanayake et al., 2024). Regulatory frameworks that permit their use in contexts adjacent to or within wild habitats on the basis of industrial composting performance are operating on a scientific premise that the peer-reviewed literature does not adequately support.

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India's convergence of acute plastic pollution and extraordinary wild medicinal plant diversity creates an urgency that is both nationally specific and globally significant. The biodiversity hotspots concentrated in the Western Ghats, Eastern Himalaya, and Andaman Islands contain thousands of wild medicinal species—many endemic and many under increasing collection pressure—in habitats simultaneously receiving plastic contamination from expanding rural–urban boundaries, agricultural intensification, and inadequate solid waste infrastructure. Dedicated microplastic monitoring within these habitats, using the bioindicator framework proposed in Section 8, would provide both the scientific baseline and the conservation trigger data necessary for evidence-based habitat management.

10. Conclusion

Wild medicinal plant habitats sit at a largely overlooked intersection of increasing plastic contamination and ongoing biodiversity loss, where impacts are now supported by consistent experimental evidence rather than assumption. This review shows that microplastics, regardless of polymer type, degrade soil structure, disrupt mycorrhizal associations, and weaken key biotic components such as earthworms and pollinators that sustain habitat function, while widely used biodegradable plastics like PLA and PBAT do not remove persistence or ecological risk under field conditions, with only limited exception for PHAs. In India, where high plastic emissions coincide with major centres of medicinal plant diversity, this interaction remains insufficiently addressed within current regulatory frameworks. Moving forward, greater emphasis is needed on field-relevant biodegradability and ecotoxicity testing, coupled with integrated bioindicator-based monitoring for early detection of ecological change, and supported by habitat-specific policy measures such as extended producer responsibility and improved waste management in biodiversity-sensitive regions. Taken together, these findings point to the need for more ecologically realistic, system-level approaches to assessing and managing plastic impacts in these habitats.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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