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Fiber-Optic Drone Tether Debris (FODTD) as an Emerging Form of War-Related Environmental Contamination

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Abstract

Contemporary armed conflicts increasingly rely on fiber-optic-guided unmanned aerial systems (UAS) as a technological response to electronic warfare. While the military effectiveness of these systems has been widely discussed, their environmental consequences have received little attention. One material by-product of this shift is the large-scale accumulation of fiber-optic drone tether debris (FODTD): polymer-coated optical fiber remnants dispersed across soils, vegetation, and surface environments in conflict zones. We propose that FODTD constitutes a distinct and previously unrecognized form of post-conflict environmental contamination. Unlike conventional military debris or generalized plastic pollution, FODTD is characterized by filamentous physical structure, high spatial dispersion, persistence in terrestrial environments, and predominantly physical modes of environmental interaction rather than acute chemical toxicity. Through abrasion, weathering, and mechanical fragmentation, FODTD can generate war-derived polymer microfibers (WDPM), linking visible tether remnants to long-term micro-scale transformations in soils and surface layers. Drawing on analogies with fishing gear debris, agricultural plastics, and other filamentous anthropogenic materials, we outline plausible environmental impact pathways and identify critical knowledge gaps. Ukraine, where fiber-optic-guided drones have been deployed intensively over multiple years, represents a first large-scale real-world setting in which this emerging form of contamination can be observed at an early stage. Recognizing FODTD as a discrete environmental object is essential for post-war land recovery, environmental monitoring, and anticipating the ecological legacies of drone-based warfare.

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Keywords: fiber-optic drone tether debris; post-conflict contamination; war-related pollution; soil contamination; filamentous plastics; microfibers; war ecology.

Key Points

1. Fiber-optic drone tether debris is proposed as a distinct source-category of war-related environmental contamination.
2. Its environmental relevance arises primarily from persistence, filamentous morphology, and diffuse spatial distribution.
3. Weathering and mechanical disturbance may transform tether remnants into war-derived polymer microfibers.
4. Ukraine provides an early-stage landscape-scale setting for observing this emerging contamination pathway.
5. Monitoring should combine visual mapping, material characterization, soil sampling, and post-conflict land-use assessment.

Introduction

Environmental consequences of armed conflicts are often addressed only after hostilities have ceased. Landmines, unexploded ordnance, heavy metals, fuel residues, and infrastructural destruction are now widely recognized as long-term legacies of war. In contrast, the environmental footprints of newly introduced military technologies frequently remain unexamined during the period of their most intensive use, even when these technologies generate persistent material traces across inhabited and cultivated landscapes.

Fiber-optic-guided unmanned aerial systems (UAS) represent one such technology. Developed to overcome electronic jamming, these systems rely on long optical fibers that physically connect the drone to its operator during flight. In recent conflicts, their deployment has expanded rapidly, resulting in extensive deposition of abandoned or severed fiber-optic tethers across terrestrial landscapes.

Despite the growing visibility of these materials in active and post-conflict environments, their environmental significance has not been conceptualized as a distinct form of contamination. Current evaluations of war-related pollution usually ignore filamentous polymer debris resulting from contemporary drone operations. This paper introduces fiber-optic drone tether debris (FODTD) as a new form of pollution, delineates its conceptual scope, delineates potential environmental pathways of impact, and lays out a research agenda for systematic study.

This study should be read within the broader context of war-related pollution and its environmental-health consequences. In Pollution and Diseases, military activity is approached as a complex environmental and public-health process affecting soils, water systems, agricultural landscapes, human communities, and animal populations. Recent publications in the journal address wartime chemical pollution, freshwater crises, soil and water transformation under military activity, and the production of human environments (1–4). The present article situates FODTD within this broader theoretical and methodological framework.

Approach and Scope

This article develops a conceptual framework based on visual documentation, emerging reports on fiber-optic drone use, and analogical evidence from microplastic, fiber, soil, and post-conflict contamination studies. It does not present direct field sampling or laboratory analysis of FODTD.

Conceptual Framework and Analysis

Definition of FODTD and WDPM

Fiber-optic drone tether debris (FODTD) is defined here as polymer-coated optical fiber remnants generated during the operation, damage, or loss of fiber-optic-guided unmanned aerial systems and subsequently deposited in terrestrial or aquatic environments.

FODTD is characterized by:

- high spatial density in conflict-affected landscapes;
- diffuse, linear, and irregular distribution rather than point-source deposition;
- persistence in soils, vegetation, and surface layers;
- absence of planned recovery, removal, or disposal mechanisms.

Through environmental exposure and mechanical stress, FODTD can fragment into smaller components. We use the term war-derived polymer microfibers (WDPM) to denote the micro-scale transformation products derived from FODTD coatings and associated polymer layers. FODTD thus represents the source-category, whereas WDPM represents its environmentally transformed micro-scale products.

Visual Documentation and Morphological Recognition

Given the unusual nature of this phenomenon, several amateur photographs are presented. The phenomenon has become widespread, and it is precisely amateur field images that most accurately reflect its scale and material presence.

Figure 1. Use of fiber-optic technology in ground-based and aerial military drones. Source: https://focus.ua/digital/700214-optovolokonnye-drony-v-ukraine-ispytali-novye-bpla-foto

Figure 2. Field example of FODTD deposited across a battlefield landscape in Ukraine. The filamentous structure, diffuse and linear spatial distribution, and frequent entanglement with vegetation distinguish FODTD from conventional point-source military debris. These materials are typically left in place without recovery or remediation, becoming persistent elements of post-conflict landscapes. Source: https://www.reddit.com/r/interestingasfuck/comments/1l082je/photo_of_a_field_in_the_ukrainian_war_zone/

In many such images, the battlefield begins to resemble a landscape entirely covered by a web-like network of filaments. The war in Ukraine has produced numerous examples of this phenomenon, documented across a wide range of publicly available sources.

Material Composition and Environmental Persistence

Natural filamentous systems as a baseline for interpretation

Filamentous structures are not alien to natural landscapes. Numerous organisms produce linear materials that interact with airflows, vegetation, and surfaces, forming spatially extended networks visible at local or landscape scales. Among the most illustrative examples are spider silk systems produced by large orb-weaving and social spider species (5–9).

These natural filament systems are adaptive, biodegradable, and biologically regulated. Their persistence depends on continuous biological maintenance, repair, and eventual decay, and their spatial distribution reflects ecological function rather than mechanical deposition.

Establishing this natural baseline is essential for distinguishing biologically integrated filamentous structures from those introduced by technological systems. While both may produce visually comparable "web-like" landscapes, their origins, material properties, maintenance mechanisms, and long-term environmental trajectories differ fundamentally.

From natural webs to anthropogenic filament landscapes

In contrast to biologically produced silk systems, filamentous structures introduced through military activity lack ecological integration and post-deployment regulation. FODTD represents a mechanically generated filament load deposited across landscapes without intent of environmental persistence, recovery, or maintenance. Once released into the environment, these filaments do not decay through biological pathways but instead persist as synthetic linear elements subject only to physical weathering and fragmentation.

The visual resemblance between natural spider webs and landscapes entangled with fiber-optic debris can be striking, particularly when filaments accumulate across vegetation or open ground. However, this resemblance is superficial. Unlike natural webs, FODTD is not spatially optimized for ecological function, nor is it constrained by biological cost. Its distribution reflects drone trajectories, tether breakage points, wind redistribution, and land-use patterns rather than adaptive design. As a result, FODTD forms heterogeneous and often chaotic filament networks that may persist for years.

This transition from adaptive, biodegradable filament systems to persistent, unmanaged synthetic ones constitutes a qualitative change in landscape structure. What seem to be similar at first glance, refer in fact to fundamentally different material regimes. Recognizing this shift is critical for understanding why fiber-optic drone debris should not be interpreted as benign or transient, but rather as a distinct category of anthropogenic filamentous contamination with long-term environmental implications.

Fiber-optic drone tethers are composite materials typically consisting of a silica-based optical core surrounded by one or more polymer coatings, most commonly acrylates, polyurethanes, epoxies, or fluoropolymers, along with stabilizers, pigments, and other functional additives (10–14). In many designs, additional reinforcing elements are incorporated to increase tensile strength and mechanical resilience during deployment (14).

While silica glass is relatively inert under most environmental conditions, polymer coatings dominate environmental interactions once the tether is deposited in terrestrial environments. Exposure to ultraviolet radiation, temperature cycling, moisture, mechanical abrasion, and repeated disturbance promotes progressive polymer aging, including surface oxidation, embrittlement, microcracking, and fragmentation (13,14). These processes are well documented for a wide range of synthetic polymers and coatings and provide transferable expectations for the environmental behavior of fiber-optic tether coatings.

Empirical data on coating degradation specifically under conflict-field conditions remain limited. However, laboratory and field studies on polymer weathering demonstrate predictable pathways of degradation, including UV-driven photo-oxidation, stress-induced cracking, and gradual release of micro- and microfibrous fragments that can be evaluated under in situ conditions (13,14). Such pathways are consistent with the formation of WDPM from FODTD through prolonged environmental exposure.

Because many conflict-affected areas do not undergo systematic debris removal, the persistence of FODTD and its transformation products is likely to be measured in years rather than weeks. Spatial heterogeneity in persistence and fragmentation rates is expected to be driven by land use, vegetation structure, soil texture, hydrological regime, and surface disturbance intensity, with soils acting as long-term sinks for polymer fragments and fibers (15).

Morphology of war-related contamination associated with FODTD

A distinct set of scientific challenges emerges when attention shifts from the mere presence of FODTD to its morphology and transformation processes. At present, this phenomenon is primarily encountered through visual documentation—field photographs, amateur images, and sporadic observations that capture extensive filamentous structures spread across battlefields. These images are striking and widely circulated, yet they remain largely descriptive. They show that a new material form is present, but not what it becomes once embedded in environmental systems.

From a morphological perspective, FODTD represents a macro-scale filamentous source material composed of polymer-coated optical fibers. Once deposited in terrestrial environments, these filaments are subjected to mechanical stress, ultraviolet radiation, moisture, temperature cycling, and repeated surface disturbance. Over time, such exposure initiates progressive degradation of polymer coatings, leading to embrittlement, surface cracking, abrasion, and fragmentation. Similar degradation pathways and surface characteristics have been observed for synthetic polymer fibers exposed to environmental and mechanical stress in aquatic and terrestrial environments (16–19). Through these processes, visible tether remnants become potential sources of WDPM that persist at micro- and sub-millimeter scales in soils and surface layers.

At present, direct morphological attribution of microfibers specifically to FODTD sources remains limited. Consequently, existing studies of polymer microfibers documented in soils, sediments, and aquatic environments serve as morphological analogues rather than definitive source confirmations. Scanning electron microscopy (SEM)–based investigations have demonstrated that polymer fibers exhibit characteristic features—such as fibrillation, surface pitting, longitudinal cracking, and irregular fracture ends—that reflect distinct pathways of mechanical abrasion and environmental aging (20–24). These features provide a critical comparative framework for interpreting the likely transformation products of fiber-optic tether coatings under field conditions.

The importance of morphology in this context is not merely descriptive. Morphological form governs how materials interact physically with soils, vegetation, water, and biota. Linear geometry, flexibility, surface roughness, and fragment size determine whether fibers remain on the surface, become entangled in vegetation, are incorporated into soil aggregates, or are redistributed by wind, water, and agricultural activity. Soil-focused SEM studies further demonstrate that fibrous particles interact with mineral matrices in ways that differ fundamentally from spherical or irregular fragments, influencing detectability, persistence, and spatial distribution.

A critical conceptual step is thus to recognize FODTD as a morphologically distinct form of war-related contamination. Without morphological characterization, FODTD is cast as incidental debris seen in photographs, rather than as a material system undergoing predictable transformations. Conversely, systematic study of its morphology—from intact tethers to microfibrous fragments—allows this phenomenon to be situated within existing frameworks of environmental materials science, soil physics, and microplastic research.

In this sense, the study of FODTD morphology marks the transition from visual recognition to scientific understanding. It acknowledges that a new form of anthropogenic contamination has been produced by contemporary warfare and that its environmental significance cannot be assessed solely through imagery or anecdotal observation. Instead, it requires explicit morphological analysis capable of linking what is seen at the surface to the long-term, less visible transformations occurring within soils and terrestrial ecosystems.

Potential Environmental Impact Pathways

The environmental significance of FODTD is likely to arise through multiple interacting pathways that operate across spatial and temporal scales. These pathways are primarily physical and physico-chemical in nature and may lead to secondary biological effects through modification of soil structure and surface processes rather than through acute chemical toxicity.

Physical effects

The filamentous structure of FODTD distinguishes it from particulate forms of plastic pollution and suggests a set of physical impact mechanisms analogous to those documented for other linear anthropogenic materials. Potential physical impacts include entanglement of wildlife, interference with agricultural machinery and land management practices, and modification of soil surface roughness and microtopography (10,25). Linear debris may also trap plant residues and organic matter, locally modifying surface energy balance, moisture retention and erosion dynamics (25,26).

Similar physical effects have been observed for abandoned fishing gear, agricultural twines and wire debris, where ecological consequences arise from persistence and mechanical interaction rather than chemical reactivity (10,25). Such analogs suggest that FODTD may exert chronic, spatially heterogeneous physical stresses on terrestrial systems even at relatively low mass loads.

In addition to direct mechanical interactions, FODTD and its transformation products may influence soil physical and chemical properties. Polymer coatings and WDPM can affect soil porosity, aggregation and water retention by introducing persistent, non-degradable linear elements into the soil matrices. Such effects have been documented for microplastics and fibrous fragments in soils, where changes in pore structure and aggregate stability can alter infiltration and gas exchange (27,28).

Polymer surfaces can also be sorbents for co-occurring contaminants such as petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and metals commonly found in post-conflict environments (29–31). While the magnitude and direction of these interactions remain context-dependent, adsorption onto polymer surfaces has the potential to modify contaminant mobility and persistence, particularly in heterogeneous soils subjected to repeated disturbance.

Biological and microbial effects

Synthetic polymers introduced into soils can serve as substrates for distinct microbial assemblages, a phenomenon widely described as the “plastisphere”. Thus, FODTD and WDPM can indirectly affect the composition of the soil microbial community, enzymatic activity, and nutrient cycling by providing new surfaces and microhabitats (30–32).

Experimental and field studies on microplastics in soils reveal biological responses are generally subtle, chronic, and spatially variable, affected by interactions between polymer type, particle morphology, soil properties, and land use (27,28,31). In the context of FODTD, such effects are likely to emerge gradually and may be difficult to detect without long-term, spatially explicit monitoring frameworks.

Integrated pathway perspective

Importantly, these physical, physico-chemical, and biological pathways should not be considered in isolation. Their interaction may produce system-level effects that are not predictable from single-factor studies. For example, changes in physical entanglement or surface roughness may alter moisture regimes, which then affect microbial activity and contaminant mobility (26,31). Integrated research designs are therefore essential to capture the cumulative and landscape-scale consequences of FODTD accumulation in post-conflict environments.

Ukraine as an Early-Stage Observational Case

Ukraine represents the first large-scale real-world setting in which FODTD accumulation can be observed at an early stage. The overlap with agricultural landscapes and inhabited areas makes this case especially relevant for post-conflict recovery.

Ukraine represents one of the first large-scale documented settings in which fiber-optic-guided unmanned aerial systems have been deployed intensively over multiple years across a wide range of terrestrial environments. During the later phase of Russia's full-scale war against Ukraine, especially from 2024–2025, fiber-optic-guided drone systems have become increasingly visible across frontline environments.

A defining feature of the Ukrainian context is the spatial overlap between current drone-related contamination and pre-existing anthropogenic pressures. Many affected regions are characterized by layered contamination histories that include industrial activities, intensive agriculture, legacy pollution from earlier conflicts, and ongoing military operations since 2014 (1,3,4). The emergence of FODTD therefore adds a new, filamentous contamination layer to landscapes that are already environmentally complex.

This layered context provides a unique opportunity to investigate how a novel source-category of contamination interacts with heterogeneous soils, land-use systems, and legacy pollutant baselines. Unlike isolated test sites or short-term military engagements, the spatial extent and duration of drone deployment in Ukraine allow observation of FODTD at an early stage of environmental persistence, before extensive remediation, burial, or transformation obscures initial distribution patterns.

Ukraine also provides strong heterogeneity in soil types, vegetation structure, hydrological regimes, and land management practices. These gradients allow comparative analysis of FODTD persistence and transformation along contrasting environmental settings, such as cultivated fields, unmanaged lands, and peri-urban environments (26). Such variability is particularly valuable for assessing spatially heterogeneous processes, including fragmentation rates, redistribution by agricultural activities, and incorporation into soil matrices.

Importantly, much of the territory affected by FODTD is inhabited and actively used. As a result, environmental processes associated with FODTD accumulation are closely coupled with land use, agricultural productivity, and post-conflict recovery planning. This distinguishes the Ukrainian case from many previous studies of war-related contamination conducted in restricted or abandoned zones and underscores the relevance of FODTD research for long-term landscape management.

Research Gaps and Monitoring Priorities

Peer-reviewed empirical studies directly quantifying FODTD as an environmental contaminant remain scarce. The issue is currently addressed mainly through policy analyses, expert commentary, preliminary assessments, and analogical evidence from microplastic, soil, and post-conflict contamination research.

Despite the visible accumulation of fiber-optic tethers in contemporary conflict zones, no established research framework treats these materials as a discrete pollution category requiring targeted assessment.

Two extensive research domains exist that, in principle, should converge on this problem but in practice remain only weakly connected. The first domain encompasses plastic pollution research, including studies on filamentous plastics and microfibers, their environmental persistence, fragmentation pathways, and interactions with soils, sediments, and biota (24,27,28,32). This literature has demonstrated that linear polymer materials can exert long-term physical, physico-chemical, and biological effects even at relatively low mass concentrations, particularly in terrestrial environments.

The second domain focuses on war-related environmental contamination. This body of work emphasizes explosive residues, metals, petroleum products, combustion-derived pollutants, fires, and infrastructure damage as the dominant environmental legacies of armed conflict. These studies have established the importance of post-conflict environmental assessment, long-term monitoring, and remediation planning but have largely overlooked non-explosive, filamentous materials generated by modern military technologies.

FODTD occupies the intersection of these two domains. It is a conflict-generated polymer contamination whose dominant environmental modes are likely to be physical, spatial, and long-term rather than acutely toxic. However, because it does not fit neatly into existing categories of either plastic pollution or military contamination, it has remained analytically invisible. As a result, baseline documentation is lacking, monitoring protocols are undeveloped, and FODTD is typically classified as incidental debris rather than recognized as a persistent, spatially structured environmental contaminant.

Recognizing this conceptual blind spot is critical. The absence of a defined category can delay environmental monitoring, obscure contamination baselines, and fragment research efforts across disciplinary boundaries. By explicitly defining FODTD as a source-category of post-conflict contamination, this paper provides a conceptual bridge between plastic/soil pollution science and war-related environmental assessment, enabling integrated approaches to observation, mapping, and long-term analysis.

Limitations

This article has several limitations. First, it is primarily a conceptual and problem-framing study. It does not present systematic field sampling, laboratory identification, chemical characterization, or quantitative measurement of FODTD in soils, water, vegetation, animal tissues, or human environments. Therefore, the article should not be interpreted as providing direct empirical proof of toxicity, disease causation, or quantified ecological risk.

Second, the proposed category of WDPM is based on a logical interpretation of the material form, expected degradation pathways, and analogies with existing research on plastic fibers, microplastics, synthetic polymers, and post-conflict environmental contamination. Direct experimental evidence demonstrating the transformation of FODTD into WDPM under battlefield or post-battlefield conditions remains necessary.

Third, the available visual materials are used for illustrative and conceptual purposes. They demonstrate the morphology and field visibility of fiber-optic tether remnants, but they do not provide a representative spatial dataset. The density, distribution, persistence, and accumulation patterns of FODTD across different Ukrainian landscapes remain unknown.

Fourth, the article focuses on Ukraine as an early and important observational context. However, when applied to other conflict zones, different drone systems, different fibre-optic cable materials or different climatic and soil conditions, the proposed framework may need to be adapted.

Fifth, wartime conditions place major methodological constraints. Access to contaminated territories may be constrained by active hostilities, landmines, unexploded ordnance, security restrictions and risks to researchers and local communities. These conditions complicate direct sampling, long-term monitoring, and independent verification.

For these reasons, the article should be understood as an initial scientific framing of an emerging contamination problem. Its main contribution is to define FODTD as a distinct source-category of war-related pollution and to propose research directions for future environmental, toxicological, ecological, veterinary, and public health studies.

Conclusions

FODTD represents an emerging form of post-conflict environmental contamination associated with contemporary drone-based warfare. Its environmental significance does not arise from acute chemical toxicity but from persistence, filamentous physical structure, diffuse spatial distribution, and interactions with existing environmental stressors. These characteristics distinguish FODTD from both conventional military debris and generalized plastic pollution.

FODTD can produce WDPM from environmental weathering and mechanical disruption, linking observable macro-scale debris to longer-term micro-scale changes in soils and surface environments. This transformation pathway highlights the importance of treating FODTD as a source-category rather than as isolated fragments or incidental debris.

Ukraine provides the first large-scale opportunity to observe this novel form of contamination at an early stage of its environmental trajectory. The spatial extent of drone deployment, combined with heterogeneous soils, land uses, and layered contamination histories, allows investigation of FODTD persistence and transformation before remediation, burial, or redistribution obscure initial patterns.

Recognizing FODTD as a discrete environmental object is a necessary step toward building appropriate monitoring strategies, analytical frameworks, and post-conflict land recovery approaches. As fiber-optic-guided systems continue to proliferate, the material traces they leave behind must be incorporated into environmental assessment not as secondary by-products of warfare, but as integral components of post-war landscapes.

Conflict of Interest

The authors declare no conflict of interest.

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Data Availability Statement

No new data were created or analyzed in this study.

References

1. Goncharova T. The Long Shadow of Wartime Chemical Pollution: Reflections on the Vietnam War and Contemporary Conflicts. Pollution and Diseases. 2025;1(January):70–78. http://doi.org/10.66659/pd.2025.003

2. Nikolaenko D. Pollution, Disease, and the Escalating Freshwater Crisis: An Integrated Review of the Mississippi and Missouri River Studies by K.R. Olson. Pollution and Diseases. 2026;2(January):5–11. http://doi.org/10.66659/pd.2026.001

3. Morton LW. Transformation of Soil and Water Properties in Agricultural Lands by Military Activity: Perspectives and Guiding Principles for the Reconstruction of War-Ravaged Agricultural Lands and Waters. Pollution and Diseases. 2026;2(April):43–64. http://doi.org/10.66659/pd.2026.004

4. Nikolaenko D. War and Peace: The Production of Human Environments. Pollution and Diseases. 2026;2(January):12–39. http://doi.org/10.66659/pd.2026.002

5. Kuntner M, Coddington JA. Discovery of the Largest Orbweaving Spider Species: The Evolution of Gigantism in Nephila. PLoS One. 2009;4(10):e7516. http://doi.org/10.1371/journal.pone.0007516

6. Agnarsson I, Kuntner M, Blackledge TA. Bioprospecting finds the toughest biological material: extraordinary silk from a giant riverine orb spider. PLoS One. 2010;5(9):e11234. http://doi.org/10.1371/journal.pone.0011234

7. Gregorič M, Agnarsson I, Blackledge TA, Kuntner M. How did the spider cross the river? Behavioral adaptations for river-bridging webs in Caerostris darwini

(Araneae: Araneidae). PLoS One. 2011;6(10):e26847 http://doi.org/10.1371/journal.pone.0026847

8. Yip EC, Powers KS, Avilés L. Cooperative capture of large prey solves scaling challenge faced by spider societies. Proceedings of the National Academy of Sciences of the United States of America. 2008;105(33):11818–11822. http://doi.org/10.1073/pnas.0710603105

9. Avilés L, Tufiño P. Colony size and individual fitness in the social spider Anelosimus eximius. The American Naturalist. 1998;152(3):403–418. http://doi.org/10.1086/286178

10. Do H-L, Armstrong CW. Ghost fishing gear and their effect on ecosystem services—Identification and knowledge gaps. Marine Policy. 2023;150:105528. http://doi.org/10.1016/j.marpol.2023.105528

11. Steinmetz Z, Wollmann C, Schaefer M, Buchmann C, David J, Tröger J, Muñoz K, Frör O, Schaumann GE. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Science of the Total Environment. 2016;550:690–705. http://doi.org/10.1016/j.scitotenv.2016.01.153

12. Rillig MC, Lehmann A, de Souza Machado AA, Yang G. Microplastic effects on plants. New Phytologist. 2019;223(3):1066–1070. http://doi.org/10.1111/nph.15794

13. Andrady AL, Barnes PW, Bornman JF, Gouin T, Madronich S, White CC, Zepp RG, Jansen MAK. Oxidation and fragmentation of plastics in a changing environment: from UV-radiation to biological degradation. Science of the Total Environment. 2022;851:158022. http://doi.org/10.1016/j.scitotenv.2022.158022

14. Janani R, Majumder D, Scrimshire A, Stone A, Wakelin E, Jones AH, Wheeler NV, Brooks W, Bingham PA. From acrylates to silicones: a review of common optical fibre coatings used for normal to harsh environments. Progress in Organic Coatings. 2023;180:107557. http://doi.org/10.1016/j.porgcoat.2023.107557

15. Zhong X, Qiang L, Cheng J, Sun Z, Hu H, Liu H, Zhang R. Aging or degradation? Transformation mechanisms of microplastics in soil environments. Applied Soil Ecology. 2025;215:106394. http://doi.org/10.1016/j.apsoil.2025.106394

16. Garcia J, di Luca C, Lopez L, de Pedro ZM, Casas JA, Muñoz M. Removal of textile microplastic fibers from water by photo-Fenton oxidation. Water Research. 2026;289:124999. http://doi.org/10.1016/j.watres.2025.124999

17. Novotna J, Tunak M, Militky J, et al. Release of microplastic fibers from polyester knit fleece during abrasion, washing, and drying. ACS Omega. 2025;10(14):14241–14249. http://doi.org/10.1021/acsomega.5c00258

18. Auyang E, Ouyang M, Laycock A, et al. Fabrication of microplastic and nanoplastic particles and fibres for use in pulmonary toxicity studies. Particle and Fibre Toxicology. 2025;22:30. http://doi.org/10.1186/s12989-025-00641-w

19. Khaleel R, Valsan G, Rangel-Buitrago N, Warrier AK. Microplastics in the marine environment of St. Mary's Island: implications for human health and conservation. Environmental Monitoring and Assessment. 2023;195(9):1034. http://doi.org/10.1007/s10661-023-11651-6

20. Ramos-Vázquez MA, Verma SK, Armstrong-Altrin JS, et al. Characterization of microplastics in marine sediments from the Gulf of Tehuantepec, Mexican Pacific. Carpathian Journal of Earth and Environmental Sciences. 2024;19(2):255–264. http://doi.org/10.26471/cjees/2024/019/296

21. Sarkar S, Diab H, Thompson J. Microplastic pollution: chemical characterization and impact on wildlife. International Journal of Environmental Research and Public Health. 2023;20(3):1745. http://doi.org/10.3390/ijerph20031745

22. Kaegi R, Philipp M, Jüngling IS, et al. Quantification of small (1–10 μm) microplastic particles in soil matrices using automated scanning electron microscopy: possibilities and limitations. Analytical and Bioanalytical Chemistry. 2025;417(27):6191–6208. http://doi.org/10.1007/s00216-025-06111-8

23. Hossain MI, Zhang Y, Haque ANMA, et al. Fibrous microplastics release from textile production phases: a brief review of current challenges and applied research directions. Materials. 2025;18(11):2513. http://doi.org/10.3390/ma18112513

24. Certini G, Scalenghe R. Anthropogenic soils are the golden spikes for the Anthropocene. The Holocene. 2011;21(8):1269–1274. http://doi.org/10.1177/0959683611408454

25. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environmental Science & Technology. 2011;45(21):9175–9179. http://doi.org/10.1021/es201811s

26. Rochman CM, Hoh E, Hentschel BT, Kaye S. Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris. Environmental Science & Technology. 2013;47(3):1646–1654. http://doi.org/10.1021/es303700s

27. de Souza Machado AA, Lau CW, Till J, et al. Impacts of microplastics on the soil biophysical environment. Environmental Science & Technology. 2018;52(17):9656–9665. http://doi.org/10.1021/acs.est.8b02212

28. de Souza Machado AA, Lau CW, Kloas W, et al. Microplastics can change soil properties and affect plant performance. Environmental Science & Technology. 2019;53(10):6044–6052. http://doi.org/10.1021/acs.est.9b01339

29. Tourinho PS, Kočí V, Loureiro S, van Gestel CAM. Partitioning of chemical contaminants to microplastics: sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation. Environmental Pollution. 2019;252(Pt B):1246–1256. http://doi.org/10.1016/j.envpol.2019.06.030

30. Zettler ER, Mincer TJ, Amaral-Zettler LA. Life in the plastisphere: microbial communities on plastic marine debris. Environmental Science & Technology. 2013;47(13):7137–7146. http://doi.org/10.1021/es401288x

31. Rillig MC, Ingraffia R, de Souza Machado AA. Microplastic incorporation into soil in agroecosystems. Frontiers in Plant Science. 2017;8:1805. http://doi.org/10.3389/fpls.2017.01805

32. MacLean J, Mayanna S, Benning LG, Horn F, Bartholomäus A, Wiesner Y, Wagner D, Liebner S. The terrestrial plastisphere: diversity and polymer-colonizing

potential of plastic-associated microbial communities in soil. Microorganisms. 2021;9(9):1876. http://doi.org/10.3390/microorganisms9091876